

THE EVOLUTION OF THE ELEMENTAL ABUNDANCES IN THE GAS AND DUST PHASES OF THE GALAXY

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ABSTRACT

We present models for the evolution of the elemental abundances in the gas and dust phases of the interstellar medium (ISM) of our Galaxy by generalizing standard models for its dynamical and chemical evolution. In these models, the stellar birthrate history is determined by the infall rate of primordial gas, and by its functional dependence on the mass surface density of the stars and gas. We adopt a two component model for the Galaxy, consisting of a central bulge and an exponential disk with different infall rates and stellar birthrate histories. Condensation in stellar winds, Type Ia and Type II supernovae, and the accretion of refractory elements onto preexisting grains in dense molecular clouds are the dominant contributors to the abundance of elements locked up in the dust. Grain destruction by sputtering and evaporative grain-grain collisions in supernova remnants are the most important mechanisms that return these elements back to the gas phase.

Guided by observations of dust formation in various stellar sources, and by the presence of isotopic anomalies in meteorites, we calculate the production yield of silicate and carbon dust as a function of stellar mass. We find that Type II supernovae are the main source of silicate dust in the Galaxy. Carbon dust is produced primarily by low mass stars in the $\sim 2 - 5 M_{\odot}$ mass range. Type Ia SNe can be important sources of metallic iron dust in the ISM.

We also analyze the origin of the elemental depletion pattern, and find that the observed core + mantle depletion must reflect the efficiency of the accretion process in the ISM. We also find that grain destruction is very efficient, leaving only $\sim 10\%$ of the refractory elements in grain cores. Observed core depletions are significantly higher, requiring significant UV, cosmic ray, or shock processing of the accreted mantle into refractory core material.

Adopting the current grain destruction lifetimes from Jones et al. (1996), we formulate a prescription for its evolution in time. We make a major assumption, that the accretion timescale evolves in a similar fashion, so that the current ratio between these quantities is preserved over time. We then calculate the evolution of the dust abundance and composition at each Galactocentric radius as a function of time.

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We find that the dust mass is linearly proportional to the ISM metallicity, and is equal to about 40% of the total mass of heavy elements in the Galaxy, independent of Galactocentric radius. The derived relation of dust mass with metallicity is compared to the observed Galactic dust abundance gradient, and to the M_{dust} versus $\log(\text{O}/\text{H})$ relation that is observed in external Dwarf galaxies.

The dependence of dust composition on the mass of the progenitor star, and the delayed recycling of newly synthesized dust by low mass stars back to the ISM give rise to variations in the dust composition as a function of time. We identify three distinct epochs in the evolution of the dust composition, characterized by different carbon-to-silicate mass ratios. Two such epochs are represented by the Galaxy and the SMC. The third is characterized by an excess of carbon dust (compared to the Milky Way galaxy), and should be observed in galaxies or star forming regions in which the most massive carbon stars are just evolving off the main sequence.

Our models provide a framework for the self-consistent inclusion of dust in population synthesis models for various pre-galactic and galactic systems, allowing for the calculation of their UV to far-infrared spectral energy distribution at various stages of their evolution.

Subject headings: Galaxy: abundances - Galaxy: evolution - Galaxy: stellar content - ISM: abundances - ISM: dust

1. INTRODUCTION

Dust particles are formed in a wide variety of astrophysical environments, ranging from quiescent stellar outflows, including various type giant and Wolf–Rayet stars, to explosive ejecta, including those of novae and Type Ia and Type II supernovae. The presence of dust in these objects and in their surrounding media affects their spectral appearance, and influences the determination of their underlying physical properties.

After their formation, dust particles are injected into the ISM where they are subjected to a variety of processes that affect their abundance and physical properties. Dust grains are subjected to destructive processes including thermal and kinetic sputtering, evaporation due to thermal spiking, and evaporative grain-grain collisions. Dust particles can also grow in the ISM by the accretion of ambient gas particles and by accumulating into larger aggregates by coagulation.

The combined effects of dust formation and processing in the ISM is manifested in the observed elemental depletion pattern, which provides an important constraint on dust evolution models. Plotting the elemental depletions as a function of their condensation temperature, Field (1974) argued that the observed correlation reflects the dust formation efficiency in the various sources. The assumption behind this model is that any further processing in the ISM will conserve

the depletion pattern that was established in the sources. Snow (1975) and Tabak (1979) showed that an equally good correlation exists between the elemental depletions and their first ionization potential, arguing that the depletion pattern reflects the accretion efficiency of the various elements in clouds. In this model all memory of the dust formation efficiency in the sources is erased, and replaced by the elemental sticking efficiency inside molecular clouds.

Accretion in clouds plays indeed an important role in determining the elemental depletion pattern. Plots depicting the depletions of select elements show that they are larger in the denser phases of the ISM, and smaller in its warmer and less dense phases (see review by Savage & Sembach 1996). This behavior is taken as evidence for the existence of two distinct dust “phases”: (1) a core, consisting of refractory material that is more immune to the various grain destruction processes operating in the ISM; and (2) a mantle, consisting of a more loosely bound material that is accreted onto preexisting cores inside dense molecular clouds.

Another interpretation of the elemental depletion pattern was suggested by Dwek and Scalo (1980), who pointed out that the sputtering threshold of various elements correlates with condensation temperature. Consequently, the elemental depletion pattern may reflect the efficiency at which various elements are sputtered from the grains in the ISM. Evidence for grain destruction in the ISM can be found from the depletions of various elements in high velocity clouds. The trend of decreasing depletions with increasing cloud velocity has been interpreted as evidence for grain destruction in shocks (Spitzer 1976, Cowie 1978; Shull 1978). Further evidence for grain destruction in the general ISM can be inferred from the IR spectrum of shock-heated dust in supernova remnants (SNRs; e.g. Dwek & Arendt 1992). Other processes that can selectively remove elements from the grains include classical evaporation, which may be facilitated by temperature fluctuations, and chemical explosions. A summary of the various depletion theories which includes further references can be found in De Boer, Jura, & Shull (1987) and Savage & Sembach (1996).

Another process that effects the properties of dust in the ISM is coagulation in dense clouds. First evidence for this process was found by Jura (1980), who concluded that the below-average visual opacity through the ρ Oph cloud complex is a result of grain coagulation in the cloud. Further evidence to that effect can be inferred from the systematic differences between the extinction curves in the diffuse intercloud medium and the outer cloud regions of the ISM (see Mathis 1990 for a review and further references). These differences have been interpreted as evidence that inside these clouds dust particles accumulate into larger aggregates. However, it is not clear whether these dust aggregates preserve this morphology in the more diffuse ISM, where even low velocity shocks can easily shatter them into their smaller grain constituents (Dominik, Jones, & Tielens 1995). In any case, the process of coagulation only alters the grain size distribution but not the mass of refractory elements locked up in dust, and will therefore not be considered in this paper.

Additional information on the sources, composition, and evolution of dust in the ISM can be

inferred from the isotopic composition of interstellar dust particles found in the meteorites (see Zinner 1996 for a recent review on the subject). The isotopic composition of these dust particles does not reflect the solar composition pattern, which represents a composition averaged over many stellar sources. Instead, their isotopic composition reflects that of their distinct stellar sources and nuclear processes that synthesized the various elements in these sources (Clayton 1982).

An important constraint on dust models is that the abundance of elements required to be locked up in solids should not exceed that available in the interstellar medium. Consequently, a self consistent dust evolution model must be part of a more general model that follows the elemental abundances and their isotopic composition in the ISM as well. Such dust evolution models should incorporate all the various processes mentioned above: the dust formation efficiencies and composition in the various sources, and the processing and cycling of dust in and between the various phases of the ISM.

Studies of the combined effects of dust formation and grain processing in the ISM were conducted by Draine & Salpeter (1979a, b), Dwek & Scalo (1979, 1980), McKee (1989), and more recently by Jones, Tielens, Hollenbach, & McKee (1994) and Jones, Tielens, & Hollenbach (1996). An important result of these studies is that grain destruction is very efficient, and that the rate at which elements are being removed from the grains in the ISM exceeds their condensation rate in the various sources. Further references on papers covering many aspects of dust formation, abundances, and evolution can be found in the volume "Interstellar Dust" (Allamandola & Tielens 1989, eds.), and in the reviews by Dorschner & Henning (1995), Tielens (1990), Tielens & Allamandola (1987), Greenberg & Hage (1990), Clayton (1982), and Draine (1990).

Various authors have constructed models to investigate different aspects of the evolution of interstellar dust. In particular, Dwek & Scalo (1980) developed a one-zone model to follow the evolution of refractory interstellar grains in the solar neighborhood, generalizing existing models for the chemical evolution of the elements (e.g. Tinsley 1980). The emphasis of their work was to examine the dependence of the interstellar depletions on the dust production efficiency in various sources and on the grain destruction lifetimes in the ISM. Their work did not include the effects of accretion in clouds on the elemental depletions, or the effect of the delayed recycling of stellar nucleosynthesis products back to the ISM. Their model was extended by Liffman & Clayton (1989) and Liffman (1990), to include a two-phase ISM in which grain growth by accretion and grain fragmentation were taken into account. The primary goals of these models was to follow the grain size distribution, and the separate evolutionary histories of the refractory grain cores and mantles in order to identify the distribution and location in the dust of the various carriers of the isotopic anomalies in meteorites. In a more recent paper, Timmes & Clayton (1996) followed specifically the evolution of SiC dust particles in the ISM, in order to study the frequency distribution of its associated isotopic anomalies in meteorites.

In all these studies, the current abundance, composition, or size distribution of dust were the primary goal of the investigations. A different approach was taken by Wang (1991a) who

emphasized the evolution of the dust abundance as a function of time. His model was essentially identical to the Dwek–Scalo model, using the instantaneous recycling approximation to describe the stellar production rate of the various elements and the dust. The evolution of the dust plays an important role in determining the opacity of galaxies during their lifetime, and has therefore important cosmological implications. The diffuse extragalactic infrared (IR) background contains the cumulative emission of redshifted starlight and starlight that has been absorbed and reradiated by dust over the cosmological history of the universe (e.g Franceschini et al. 1996). It is therefore affected by dust evolution in galaxies. Furthermore, the presence of dust at high redshift can lead to erroneous conclusions regarding galaxy number counts and the evolution of quasars (Wang 1991b, Pei & Fall 1993). In an interesting test of dust evolution models, Ute & Ferrara (1997) correlated the metallicity of a sample of dwarf galaxies with their dust content. The galaxy sample contains objects with different metallicities, and may therefore be providing a look at the temporal history of the dust evolution in these objects.

The current paper extends several aspects of the studies described above. The model presented here consists of three distinct components: (1) *a dynamical model for the evolution of the stellar and gaseous contents of the Galaxy*. The disk mass grows by primordial infall to attain its present mass and morphology. Different infall rates are assumed for the bulge and disk component of the Galaxy. The stellar birthrate history is determined by the infall rate and by the stellar and ISM mass densities of the disk; (2) *a chemical evolution model for the elements*. The formalism used here is essentially identical to the one used by Matteucci & Greggio (1986), Matteucci & François (1989), and more recently by Timmes, Woosley, & Weaver (1995). It follows the evolution of the elemental abundances, taking into account the delayed recycling of the elements back into the ISM; and (3) *a model for the evolution of the dust*. The basic equations describing the chemical evolution of the elements are generalized to include that of the dust. The dust is assumed to be either carbon rich or silicate type dust. Two processes affecting the evolution of the dust, but not that of the elements, are included in the model: grain destruction by expanding SNRs, and grain growth by accretion in molecular clouds. The ISM is considered to be a one–phase medium. Grain destruction and accretion rates are therefore effective rates that represent values averaged over the cycling time of the dust between the various ISM phases. Grain destruction in clouds by evaporative grain-grain collisions have a negligible effect on the dust evolution and are ignored in this study. We also only follow the *mass* of dust in the ISM, and do not calculate the evolution of the grain size distribution, as has been recently attempted by O’Donnell & Mathis (1997). We feel that such details are not warranted at this time, considering current uncertainties regarding the nature of interstellar dust particles (Dwek 1997). One aspect that is followed in detail in the current model is the delayed recycling of the elements and the dust back into the ISM. This delay has important observational consequences, and is responsible for changes in the mixture of dust composition over time.

The mathematical formalism of the model is described in detail in §2. The evolution of the Galactic disk and that of the elemental composition are presented in §3 and §4, respectively.

§5 describes the formation of dust and calculates the dust production rate by various sources. Timescales for grain destruction by SNRs, and their time evolution are presented in §6. The section includes also an brief discussion of the starburst galaxy M82, for which we derive rough estimates of grain destruction lifetimes. Grain lifetimes for growth by accretion, and their time evolution are presented in §7. Model results are presented in §8, and a brief summary and discussion of the paper is presented in §.

2. MATHEMATICAL FORMULATION

2.1. The Chemical Evolution of the ISM

We consider a multi-zone model for the chemical evolution of our Galaxy, in which star formation, gas infall, and expanding SNRs play the dominant role in determining the abundances of the various elements in the gas and solid phases of the ISM. Unlike conventional chemical evolution models (e.g. Matteucci 1997), we distinguish between the abundances of the elements in the gas and solid phases of the ISM. We therefore define $\sigma_{ISM}(A, r, t)$ as the *total* (gas + dust) surface mass density of a stable element A that is located at time t at Galactocentric radius r . The ISM mass surface density, $\sigma_{ISM}(r, t)$, of *all* elements A is given by the sum:

$$\sigma_{ISM}(r, t) = \sum_{\{A\}} \sigma_{ISM}(A, r, t) \quad (1)$$

The equations for the evolution of $\sigma_{ISM}(r, t)$ and $\sigma_{ISM}(A, r, t)$ at a given Galactocentric radius r and time t are given by:

$$\begin{aligned} \frac{d\sigma_{ISM}(r, t)}{dt} &= -\mathcal{B}(r, t) \\ &+ \int_{M_l}^{M_u} \mathcal{B}(r, t - \tau(M)) \phi(M) \left[\frac{M_{ej}(M, Z)}{M_{av}} \right] dM \\ &+ \left(\frac{d\sigma(r, t)}{dt} \right)_{inf} \end{aligned} \quad (2)$$

and

$$\begin{aligned} \frac{d\sigma_{ISM}(A, r, t)}{dt} &= -Z_{ISM}(A, r, t) \mathcal{B}(r, t) \\ &+ \int_{M_l}^{M_u} \mathcal{B}(r, t - \tau(M)) \phi(M) \left[\frac{M_{ej}(A, M, Z)}{M_{av}} \right] dM \\ &+ \left(\frac{d\sigma_A(r, t)}{dt} \right)_{inf} \end{aligned} \quad (3)$$

where $\mathcal{B}(r,t)$ is the stellar birthrate in units of $M_\odot \text{ pc}^{-2} \text{ Gyr}^{-1}$, and $\tau(M)$ is the lifetime of a star of mass M . The function $\phi(M)$ is the stellar mass spectrum (SMS), defined as the *number* of stars born per unit mass, and normalized to unity in the $\{M_l, M_u\}$ mass interval. $M_{ej}(M,Z)$ and $M_{ej}(A,M,Z)$ are, respectively, the total mass and the mass of element A , that are ejected by a star of mass M and initial metallicity Z back into the ISM, M_{av} is the SMS-averaged mass of the newly born stars, and $(\frac{d\sigma}{dt})_{inf}$, is the infall rate of primordial gas into the Galaxy. Finally, the parameter $Z_{ISM}(A,r,t)$ in equation (3) is the mass fraction of a given element in the ISM, defined as:

$$Z_{ISM}(A,r,t) \equiv \frac{\sigma_{ISM}(A,r,t)}{\sigma_{ISM}(r,t)} \quad (4)$$

Further details on the choice of SMS and various related parameters are given in §3 below.

Following Matteucci & Greggio (1986; see also Matteucci & François 1989; Chiappini, Matteucci, & Gratton 1997; and Timmes, Woosley, & Weaver 1995), we will rewrite equation (3) as an explicit sum of its various contributions:

$$\begin{aligned} \frac{d\sigma_{ISM}(A,r,t)}{dt} = & - Z_{ISM}(A,r,t) \mathcal{B}(r,t) \\ & + \int_{M_l}^{M_{b1}} \mathcal{B}(r,t - \tau(M)) \phi(M) \left[\frac{M_{ej}(A,M,Z)}{M_{av}} \right] dM \\ & + \beta \left(\frac{M_{ej}^I(A)}{M_{av}} \right) \int_{M_{b1}}^{M_{b2}} \phi(M_b) dM_b \int_{\mu_m}^{\frac{1}{2}} f(\mu) \mathcal{B}(r,t - \tau(\mu M_b)) d\mu \\ & + (1 - \beta) \int_{M_{b1}}^{M_{b2}} \mathcal{B}(r,t - \tau(M)) \phi(M) \left[\frac{M_{ej}(A,M,Z)}{M_{av}} \right] dM \\ & + \int_{M_{b2}}^{M_u} \mathcal{B}(r,t - \tau(M)) \phi(M) \left[\frac{M_{ej}(A,M,Z)}{M_{av}} \right] dM \\ & + \left(\frac{d\sigma}{dt} \right)_{inf} \end{aligned} \quad (5)$$

The first term in equation (5) represents the removal rate of element A from the ISM due to astration. The second term represents the enrichment rate of the element due to stars in the $\{M_l, M_{b1}\}$ mass range. The third equation represents the enrichment rate of A due to binary systems that become Type Ia supernovae, where $M_{ej}^I(A)$ is the mass of element A synthesized in the explosion, and M_{b1} and M_{b2} are, respectively, the lower and upper mass limits of binary systems that become Type Ia SNe. The parameter β determines the relative rates of Type Ia to Type II events, and will be discussed in more detail below. The fourth term represents the enrichment due to binary systems that do not undergo Type Ia events, and stars with masses $\geq M_w$ that become Type II SNe. The fifth term represents the enrichment rate of element A due to massive stars ($M \geq M_w$) that become Type II SNe, and the final term is the accretion rate of element A onto the disk due to infall. Throughout this work, we assume that the infalling gas has primordial abundances. We note that the mathematical formalism is unchanged in the presence of *outflows*.

The last term will then simply represent the net rate at which the abundance of element A is changing in the disk due to combined effect of accretion and outflow.

2.2. The Chemical Evolution of the Dust

The evolution of an element A in the dust can be described in a way similar to that of the elements in the ISM (eq. 5) as:

$$\begin{aligned}
\frac{d\sigma_{dust}(A, r, t)}{dt} = & -Z_{dust}(A, r, t) \mathcal{B}(r, t) \\
& + \int_{M_l}^{M_{b1}} \mathcal{B}(t - \tau(M)) \phi(M) \left[\frac{\delta_{cond}^w(A) M_{ej}(A, M, Z)}{M_{av}} \right] dM \\
& + \beta \left(\frac{\delta_{cond}^I(A) M_{ej}(A)}{M_{av}} \right) \int_{M_{b1}}^{M_{b2}} \phi(M_b) dM_b \int_{\mu_m}^{\frac{1}{2}} f(\mu) \mathcal{B}(r, t - \tau(\mu M_b)) d\mu \\
& + (1 - \beta) \int_{M_{b1}}^{M_{b2}} \mathcal{B}(r, t - \tau(M)) \phi(M) \left[\frac{\delta_{cond}^w(A) M_{ej}(A, M, Z)}{M_{av}} \right] dM \\
& + \int_{M_{b2}}^{M_u} \mathcal{B}(r, t - \tau(M)) \phi(M) \left[\frac{\delta_{cond}^{II}(A) M_{ej}(A, M, Z)}{M_{av}} \right] dM \\
& - \sigma_{dust}(A, r, t) / \tau_{SNR}(A, r, t) \\
& + \sigma_{dust}(A, r, t) \left(1 - \frac{\sigma_{dust}(A, r, t)}{\sigma_{ISM}(A, r, t)} \right) / \tau_{accr}(A, r, t) \\
& - \left(\frac{d\sigma_{dust}(A, r, t)}{dt} \right)_{outf}
\end{aligned} \tag{6}$$

where

$$Z_{dust}(A, r, t) \equiv \frac{\sigma_{dust}(A, r, t)}{\sigma_{ISM}(r, t)} \tag{7}$$

is the mass fraction of element A locked up in dust, and the parameters $\delta_{cond}^w(A)$, $\delta_{cond}^I(A)$, and $\delta_{cond}^{II}(A)$ represent the condensation efficiency of the element A in stellar winds, Type I SNe, and Type II SNe, respectively. Eq (6) introduces two new terms that affect the evolution of dust in the ISM: (1) the sixth term in the equation, which is the rate at which the element A is returned to the gas phase as the dust is destroyed by SNRs; and (2) the seventh term, which represents the rate at which an element A is removed from the gas phase by accretion onto *preexisting* dust particles in molecular clouds. The parameters $\tau_{SNR}(A, r, t)$, and $\tau_{accr}(A, r, t)$, are, respectively, the timescales for these processes, and will be discussed in more detail below.

3. THE EVOLUTION OF THE GALACTIC DISK

3.1. The Infall Model

We adopt a dynamical model for the Galaxy, which starts from a zero mass disk that grows by accretion of primordial gas from its surrounding medium. The present ($t=t_G$) disk morphology consists of a central bulge, and an exponential disk. The present mass distribution of the disk is assumed to be exponential of the form:

$$\sigma_{disk}(r, t_G) = \sigma_{\odot} \exp\left(-\frac{r - R_{\odot}}{R_{disk}}\right) \quad 0 \leq r(kpc) \leq 15 \quad (8)$$

where σ_{\odot} , is the current mass density of the disk at the solar circle, and R_{disk} is the exponential scale length of the disk. Current estimates for σ_{\odot} are in the $40 - 80 \text{ M}_{\odot} \text{ pc}^{-2}$ range (Gould, Bahcall, & Flynn 1996). Here we adopt a compromise value of $\sigma_{\odot} = 60 \text{ M}_{\odot} \text{ pc}^{-2}$. The scale length of the disk is taken to be 3.5 kpc, which is a fit to the Bahcall & Soneira (1980) model, and was also used by Wainscoat et al. (1992) in their faint source model of the Galaxy. The total mass of the disk, integrated out to a radius of 15 kpc is $M_{disk} \approx 2\pi R_{disk}^2 \sigma_{\odot} \exp(R_{\odot}/R_{disk})$, where R_{disk} is in kpc. For a value of $\sigma_{\odot} = 60 \text{ M}_{\odot} \text{ pc}^{-2}$, the disk mass is $5.2 \cdot 10^{10} \text{ M}_{\odot}$.

For the bulge we adopt a oblate spheroidal mass distribution of the form $\rho(x) = \rho_0 \exp(-x^2)$ (model G0 in Dwek et al. 1995), up to a galactic radius of 2 kpc, which is about equal to the corotation radius beyond which stable orbits cannot exist (Binney et al. 1991). The disk-projected mass surface density of this oblate spheroid can be written as:

$$\begin{aligned} \sigma_{bulge}(r, t_G) &= \sigma_0 \exp\left(-\frac{r^2}{R_{bulge}^2}\right) \quad \text{for } r \leq 2 \text{ kpc} \\ &= 0 \quad \text{for } r \geq 2 \text{ kpc} \end{aligned} \quad (9)$$

where σ_0 is the central mass density of the bulge, and R_{bulge} a scaling parameter. The total mass of the bulge, integrated to a distance of 2 kpc, is $M_{bulge} = \pi R_{bulge}^2 \sigma_0 \left[1 - \exp(-4/R_{bulge}^2)\right]$, where R_{bulge} is in kpc. From a fit of the sky-projected intensity distribution of the oblate spheroid to the observed near-IR intensity of the bulge observed by the *COBE*/DIRBE, Dwek et al. (1995) find a value of $R_{bulge} \approx 1.3 \text{ kpc}$, and a total photometrically deduced bulge mass of $\approx 1.3 \cdot 10^{10} \text{ M}_{\odot}$. This mass is very similar to the dynamically deduced bulge mass of $\approx 1 \cdot 10^{10} \text{ M}_{\odot}$ (Kent 1992). Adopting a bulge mass of $1.3 \cdot 10^{10} \text{ M}_{\odot}$, we get that the resulting central mass density for the bulge is $\sigma_0 = 2.7 \cdot 10^3 \text{ M}_{\odot} \text{ pc}^{-2}$.

The total surface mass density of the disk at the present epoch, $\sigma_{tot}(r, t_G)$ is:

$$\sigma_{tot}(r, t_G) = \sigma_{disk}(r, t_G) + \sigma_{bulge}(r, t_G) \quad (10)$$

giving a total Galactic mass of $6.5 \cdot 10^{10} \text{ M}_{\odot}$. We note that unlike TWW95, we did not impose any

continuity between the values or slopes of the surface mass densities of the disk and bulge at the co-rotation radius, since it has no physical basis.

The Galactic infall rate at each distance r is assumed to be decreasing exponentially with time:

$$\left(\frac{d\sigma(r,t)}{dt}\right)_{inf} = A(r) \exp\left[-\frac{t}{\tau_{inf}(r)}\right] \quad (11)$$

where $\tau_{inf}(r)$ is a radially dependent timescale of the form given by CMG96:

$$\begin{aligned} \tau_{inf}(r) &= 0.4615 \, r(kpc) + 0.077 \, \text{Gyr} \quad \text{for } r \geq 2 \, kpc \\ &= 1 \, \text{Gyr} \quad \text{for } r \leq 2 \, kpc \end{aligned} \quad (12)$$

Equation (12) gives an infall rate of 1 Gyr for the formation of the bulge, and an infall rate of 6 Gyr in the solar neighborhood.

3.2. The Stellar Birthrate

We will assume that the stellar birthrate $\mathcal{B}(r,t)$, defined here as the mass of stars born per unit disk area per unit time, can be written as the product:

$$\begin{aligned} \mathcal{B}(r,t) &= \mathcal{C}(r,t) \int_{M_l}^{M_{up}} M \phi(M) dM \\ &= \mathcal{C}(r,t) M_{av} \end{aligned} \quad (13)$$

where $\phi(M)$, the stellar mass spectrum (SMS), is the number of stars born per unit mass and is normalized to unity in the $\{M_l, M_{up}\}$ mass interval, $\mathcal{C}(r,t)$ is a stellar creation function, and M_{av} is the average mass of stars in the $\{M_l, M_{up}\}$ mass interval. Details of the SMS are described in §3.3 below. In particular, $\mathcal{R}(r,t, M_1, M_2)$, the *number* of stars born in the $\{M_1, M_2\}$ mass interval per unit disk area per unit time can be written in terms of $\mathcal{B}(r,t)$ as:

$$\begin{aligned} \mathcal{R}(r,t, M_1, M_2) &= \mathcal{C}(r,t) \int_{M_1}^{M_2} \phi(M) dM \\ &= \frac{\mathcal{B}(r,t)}{M_{av}} \int_{M_1}^{M_2} \phi(M) dM \end{aligned} \quad (14)$$

Following Dopita & Ryder (1994) and Ryder (1995) we will write the stellar birthrate in the form $\mathcal{B} \sim \sigma_{tot}^k \sigma_{ISM}^n$. In the classical Schmidt law: $\mathcal{B} \sim \rho_{gas}^2$, where ρ_{gas} represents the number density of the gas. The additional dependence on the total mass density of the disk proposed by Dopita & Ryder (1994) presumably includes the feedback effects of the star-formation/death processes on the birthrate. The birthrate, in units of $M_\odot \text{ pc}^{-2} \text{ Gyr}^{-1}$, is then:

$$\mathcal{B}(r, t) = \nu \sigma_{tot}(r, t) \left(\frac{\sigma_{tot}(r, t)}{\sigma_{tot}(R_{\odot}, t)} \right)^k \left(\frac{\sigma_{ISM}(r, t)}{\sigma_{tot}(r, t_G)} \right)^n \quad (15)$$

where ν is the star formation efficiency factor in Gyr^{-1} . At each galactic radius r , the ISM mass surface density is normalized to the total mass surface density at the current epoch, t_G , and at each epoch t , the total mass surface density is normalized to that in the solar vicinity. The present birthrate at the solar circle is thus given by:

$$\mathcal{B}(R_{\odot}, t_G) \equiv \mathcal{B}_{\odot} = \nu \sigma_{\odot} \left(\frac{\sigma_{ISM}(R_{\odot}, t_G)}{\sigma_{\odot}} \right)^n \quad (16)$$

where the last term represents the present ISM mass fraction in the solar vicinity. The present birthrate as a function of Galactic radius is given by:

$$\mathcal{B}(r, t_G) = \nu \sigma_{tot}(r, t_G) \left(\frac{\sigma_{tot}(r, t_G)}{\sigma_{\odot}} \right)^k \quad (17)$$

where as in equation (8), $\sigma_{\odot} \equiv \sigma_{tot}(R_{\odot}, t_G)$.

The observational constraints on \mathcal{B}_{\odot} , σ_{\odot} , and the present day mass fraction of the ISM (see Table 1) constrain the allowable values of ν , k , and n . Following CMG96, we adopted the values of $\nu = 1.0 \text{ Gyr}^{-1}$, and $\{k, n\} = \{0.5, 1.5\}$ in this paper.

3.3. The Evolution of the Disk and the ISM

A characteristic of the infall model is the gradual buildup of the disk from zero mass to its present composition of stars and gas. The relative mix of stars and gas is determined by the exact prescription for the stellar birthrate, and the flux of infalling material. Figure 1 presents the stellar birthrate per unit surface area at the center of the Galactic bulge and in the solar circle, as a function of time. Also plotted in the figure is the disk averaged value of the stellar birthrate. Stellar birthrates increase initially, as more material is accreted onto the Galaxy, decreasing at a later epoch as the infalling gas is converted to stars. Since the infall timescale onto the bulge is only 1 Gyr, star formation peaks at the Galactic center at an early epoch of about 0.6 Gyr. At the solar circle, where the infall timescale was taken to be 4 Gyr, the stellar birthrate peaks at about 6 Gyr. Figure 2 depicts the radial dependence of the stellar birthrate as a function of Galactocentric radius. Figure 3 shows the evolution of the surface density of the stars and the ISM at the Galactic center and the solar circle as a function of time. Table 2 summarizes the various model output parameters at the solar circle. As shown in the table, the model reproduces the observational constraints in the solar neighborhood.

4. THE EVOLUTION OF THE ELEMENTS

The evolution of the elements is determined by the stellar mass spectrum (SMS), and the stellar nucleosynthesis yield.

4.1. The Stellar Mass Spectrum (SMS)

The SMS was originally parameterized as a single power law of the form $\sim M^{-\alpha}$ with $\alpha = 2.35$ over the 0.5 to $10 M_{\odot}$ mass interval (Salpeter 1955). Subsequent studies (Miller & Scalo 1979; Scalo 1986) showed that the Salpeter SMS significantly overestimates the number of stars with masses below $\sim 1 M_{\odot}$, and that its slope at higher masses is somewhat steeper than the Salpeter one, and characterized by a value of $\alpha = 2.7$ instead. The slope for $M > 1 M_{\odot}$ was confirmed by subsequent studies (Rana & Basu 1992) who derived a value of $\alpha = 2.6$, however, Van Buren (1985) derived a somewhat shallower slope with an $\alpha = 2.0$. Recent studies of Tsujimoto et al. (1997) suggest a slope of α between 2.3 and 2.6 above $1 M_{\odot}$. The shape of the SMS is more uncertain at lower masses. Scalo's results suggests the existence of a distinct maxima in the SMS around $\sim 0.2 M_{\odot}$, decreasing at lower masses, with $\alpha \approx 1.6$. The results of Tinney (1993) suggest a flattening of the SMS in the ~ 0.12 to $0.25 M_{\odot}$ mass range with a possible upturn at lower masses, whereas the studies of Kroupa, Tout, & Gilmore (1993) suggest a shallower power with an average value of $\alpha = 1.6$ between 0.1 and $1.0 M_{\odot}$. Fortunately, the results of our calculations are not sensitive to the shape of the SMS below $\sim 1 M_{\odot}$. The functional form finally adopted for the SMS in the $\{M_l, M_u\} = \{0.1 M_{\odot}, 40 M_{\odot}\}$ mass range is:

$$\begin{aligned} \phi(M) &= C_1 & for & 0.1 \leq M/M_{\odot} \leq 0.3 \\ &= C_2 M^{-1.6} & for & 0.3 \leq M/M_{\odot} \leq 1 \\ &= C_3 M^{-2.6} & for & 1 \leq M/M_{\odot} \leq 40 \end{aligned} \quad (18)$$

where the constants C_1 , C_2 , and C_3 are determined from the normalization:

$$\int_{M_l}^{M_u} \phi(M) dM = 1 \quad (19)$$

and by the requirement that $\phi(M)$ be continuous at $M = 0.3$ and $1 M_{\odot}$.

4.2. The Type I and II Supernovae Rate

Type II SNe result from the collapse of the iron core of stars with masses above a value M_w , taken here to be equal to $8 M_{\odot}$. The rate of SN II, in units of $\text{pc}^{-2} \text{Gyr}^{-1}$ is therefore given from equation (14) by:

$$\mathcal{R}_{SNII}(r, t) = M_{av}^{-1} \int_{M_w}^{M_u} \mathcal{B}(r, t - \tau(M)) \phi(M) dM \quad (20)$$

Type Ia supernovae are the result of thermonuclear explosions in accreting white dwarfs in binary systems (e.g. Hachisu, Kato, & Nomoto 1996, and references therein). Let $M_b = m + M$ be the mass of the binary system, where $m \leq M$, and let $\mu \equiv m/M_b$. The SN Ia rate, \mathcal{R}_{SNI} , given in $\text{pc}^{-2} \text{Gyr}^{-1}$, can then be written as the following double integral (Greggio & Renzini 1983, Matteucci & Greggio 1986):

$$\mathcal{R}_{SNIa}(r, t) = \beta M_{av}^{-1} \int_3^{16} \phi(M_b) dM_b \int_{\mu_m}^{1/2} f(\mu) B(r, t - \tau(M = \mu M_b)) d\mu \quad (21)$$

where $\mu_m = \max\{M_{TO}(t)/M_b, (M_b - M_w)/M_b\}$, and M_{TO} is the main-sequence turnoff mass at time t . The function $f(\mu) = 24\mu^2$ is normalized to unity in the $\{0, \frac{1}{2}\}$ interval, and represents the probability that a binary system will have a mass ratio μ . Equation (21) assumes a minimum and maximum binary mass of $M_{b1} = 3 M_\odot$, and $M_{b2} = 2 M_w = 16 M_\odot$, respectively.

The parameter β determines the value of $R_{Ia/II} \equiv \mathcal{R}_{SNIa}(R_\odot, t_G)/\mathcal{R}_{SNII}(R_\odot, t_G)$, the currently observed ratio of SN Ia to SN II events. The value of $R_{Ia/II}$ can span a wide range of values, and Rocca-Volmerange & Schaeffer (1990) considered the effects of varying $R_{Ia/II}$ from 0.25 to 1.22 on Galactic chemical evolution. CMG96 found that a value of $R_{Ia/II} = 0.37$ best reproduces the elemental abundances, whereas Tsujimoto et al. (1995) and TWW95 derive similar values of $R_{Ia/II} = 0.16$ for the relative SN Ia and SN II rates. In our model, the value of β was adjusted until it produced a good fit to the solar abundances at the epoch the solar system was formed.

4.3. Nucleosynthesis Yields

Stellar nucleosynthesis yields are commonly divided into four categories: (1) yields from low-mass stars ($M \leq M_w = 8 M_\odot$) that return mass quiescently in the form of stellar winds and planetary nebulae back to the ISM; (2) yields from binary stars in the $\{M_{b1}, M_{b2}\}$ mass range that become Type Ia SNe; (3) yields from stars with masses $\geq M_w$ that become Type II SNe; and (4) yields from stars with masses $\gtrsim 40 M_\odot$, whose evolution is dominated by stellar mass loss.

Yields for the stars in the 1 to 8 M_\odot mass range were taken from Renzini & Voli (1981; hereafter RV81) from their tabulated values for metallicities of $Z = 0.004$ and $Z = Z_\odot = 0.020$, with $\alpha = 3/2$ and $\eta = 1/3$.

For Type Ia SNe we used the yields for model W7, tabulated in Thielemann, Nomoto & Hashimoto (1993), which are based on the model W7 of Nomoto, Thielemann & Yokoi (1984), and Thielemann, Nomoto, & Yokoi (1986).

For stars in the 11 to 40 M_{\odot} mass range we adopted the post-explosive nucleosynthesis of Woosley & Weaver (1995). In addition to the metallicity of the progenitor stars, the yields depend on the explosion energy, and following Timmes, Woosley & Weaver (1995) we adopted models "A" for stars with initial masses below 25 M_{\odot} , and models "B" for the 30, 35, and 40 M_{\odot} stars.

For the primordial abundances of the infalling gas we adopted the Big Bang composition with $Z(H) = 0.77$, and $Z(He)=0.23$ (Olive & Steigman 1995).

4.4. Observational Tests of the Chemical Evolution Model

Viable chemical evolution models should be able to reproduce the following observational constraints (e.g. Edvardsson et al. (1993): (1) the observed solar abundances at the time the solar system formed; (2) the observed age-metallicity relation; (3) the Galactic abundance gradient; (4) the frequency distribution of metallicity (also known as the G-dwarf problem); and (5) the $[\alpha/Fe]$ versus $[Fe/H]$ abundance trend. Figure 4 tests our model against these various constraints, illustrating that the model reproduces them as well as other comparable models (e.g CMG97 or TWW95). Figure 4a shows that the model reproduces the elemental abundances at the time the sun was formed, with the exception of N. Nitrogen is overproduced as a result of the HBB process. The overproduction of N will not effect the results of this paper, since N is neither condensed in stellar outflows, nor accreted onto dust in the ISM. Figure 4b compares the model age–metallicity relation versus observational constraints, and Figure 4c compares the metallicity frequency predicted by the model to that inferred from G-dwarf population. All these tests do not depend on the fraction of the metals in the ISM is locked up in dust. However, the Galactic metal abundance gradient does, since the observations sample only the gas phase abundance of the elements in the ISM. Figure 4d plots the total ISM $[Fe/H]$ abundance, $[Fe/H] \equiv (Fe/H)/(Fe/H)_{\odot}$, as well as the gas phase $[Fe/H]$ abundance, versus Galactic radius. Also plotted in the figure are the observational constraints. The figure clearly shows the improvement in the fit when the fraction of the iron locked up in the dust is subtracted from the total Fe abundance. The final observational test, the $[\alpha/Fe]$ versus $[Fe/H]$ abundance trend, has been discussed extensively elsewhere (TWW95). Since we adopted similar stellar SMS and abundance yields, our trends should be similar to theirs. Figure 5 shows the current SN Ia and SN II supernovae rates at these locations as a function of time. As shown in Table 2, the current SN II and SN Ia rates are consistent with observational constraints.

5. THE EVOLUTION OF THE DUST

5.1. Dust Formation

Dust formation takes place in a variety of astronomical sources that can be broadly divided into two categories: sources that undergo quiescent mass loss, and sources that return their ejecta explosively back to the ISM. Below we present the various lines of evidence for the formation of dust in the various sources. The prescription used to calculate the dust production yield in the various sources is given in §3.8 and a comparison between the calculated dust production/destruction rates at the current epoch and observational estimates is presented in Table 3.

5.1.1. Quiescent Formation: Low-Mass Stars, $M < 8 M_{\odot}$

The cool atmospheres of late-type giant and supergiant stars provide an ideal environment for the nucleation and growth of refractory grains (e.g. Sedlmayr 1989 and references therein). The presence of dust in these objects is inferred from the presence of an excess of IR emission above the underlying stellar continuum, and from the extinction, scattering, and polarization of the underlying stellar UV-visual photons. The composition of the dust particles around these stars is inferred from their spectral features: the 9.7 and 18 μm silicate features, the 11.3 μm SiC feature, a broad $\sim 30 \mu\text{m}$ MgS feature, the ice absorption feature at 3.1 μm , and a featureless spectrum usually associated with graphite or amorphous carbon dust. The type of dust that forms in the outflowing matter depends on the C/O ratio in the ejecta. When $\text{C/O} > 1$, all the oxygen is tied up in CO molecules, and the newly formed grains will be carbon rich. If conversely, $\text{C/O} < 1$, the excess oxygen will combine with other refractory elements to form silicate type material (e.g. Whittet 1989, and references therein). There is observational evidence supported by laboratory data that MgS and sulfites form when $\text{C/O} \approx 1$ (Nuth et al. 1985), but these dust species are relatively rare, and will not be considered here.

5.1.2. Quiescent Formation: Wolf-Rayet Stars

High mass stars ($M \gtrsim 40 M_{\odot}$) can lose mass at a rate of $\sim (2 - 10) 10^{-5} M_{\odot} \text{ yr}^{-1}$ (Abbott & Conti 1987; van der Hucht 1992), which will have a significant effect on their structure and evolution (e.g. Maeder 1991). Above a critical mass loss rate these stars will strip off their H-rich envelope, exposing the underlying cores. Such stripped cores will appear as Wolf-Rayet stars of type N if the exposed material is N-rich, and of type WC, if the exposed material is C-rich. However, although rapid mass loss is a common characteristic of all WR stars, only the coolest WC stars (WC8 and WC9) exhibit an IR excess that can be attributed to the formation of dust in their atmosphere (Cohen, Barlow, & Kuhl 1975; Williams, van der Hucht, & Thé 1987). The dust spectrum is featureless, suggesting carbon type dust, consistent with the enrichment of carbon in the stellar ejecta. Since these stars are rare, their contribution to the overall production of interstellar dust is not expected to be significant. WR originate from stars with masses in excess of

$\sim 40 M_{\odot}$, and are therefore by a factor of ~ 20 less frequent than Type II SNe. For a local Type II rate of $0.024 \text{ pc}^{-2} \text{ Gyr}^{-1}$ (see Table 2), we get a WR rate of $\sim 2 \cdot 10^{-3} \text{ pc}^{-2} \text{ Gyr}^{-1}$. Adopting a total wind mass of $\sim 10 M_{\odot}$, and a carbon dust-to-mass ratio of ~ 0.02 , the total carbon dust production rate from WR stars is $\sim 2 \cdot 10^{-4} M_{\odot} \text{ pc}^{-2} \text{ Gyr}^{-1}$.

5.1.3. *Following Explosive Conditions: Novae*

Many novae eruptions exhibit a spectacular evolution of their lightcurve characterized by the development of a steep decline at UV-visual wavelengths, about 3 to 4 months after the outburst, accompanied by a rapid rise at infrared wavelengths (see Gehrz 1988 for an extensive review on the subject). This behavior in the lightcurve was interpreted as evidence for the formation of dust in the nova ejecta (Geisel, Kleinmann, & Low 1970) and first modelled by Clayton & Hoyle (1976) and Clayton & Wickramasinghe (1976). The dust formation interpretation was challenged by Bode & Evans (1981), who suggested that the rise in the IR lightcurve is the result of the delayed reradiation of the UV-optical light by pre-existing circumstellar dust (an infrared echo). However, the echo model fails to explain various aspects of the nova development, and the dust formation scenario is now the most commonly accepted explanation for the IR development in novae (Gehrz 1988).

Novae are not likely to be important sources of interstellar dust. Novae are about 4000 times more frequent than Type Ia SNe (van den Bergh & Tamman 1991). With a local SN Ia rate of $3.7 \cdot 10^{-3} \text{ pc}^{-2} \text{ Gyr}^{-1}$ (see Table 2), the typical nova rate is $\sim 15 \text{ pc}^{-2} \text{ Gyr}^{-1}$. Most novae produce carbon dust. Dust masses in the nova ejecta range from $\sim 2 \cdot 10^{-8}$ to $\sim 4 \cdot 10^{-7} M_{\odot}$ (Gehrz 1988). Adopting an average value of about $\sim 2 \cdot 10^{-7}$, we get that the dust production rate of novae is $\sim 3 \cdot 10^{-6} M_{\odot} \text{ pc}^{-2} \text{ Gyr}^{-1}$. Silicate production has been observed only in one nova, which developed an optically thin dust shell. The silicate production yield of novae is therefore smaller than that of carbon. In spite of their negligible contribution to the total dust production rate, novae condensates may be important sources of some isotopic anomalies in meteorites.

5.1.4. *Following Explosive Conditions: Type II Supernovae*

Supernovae have been suggested as important sources of interstellar dust long before the existence of any supporting evidence (Cernuschi, Marsicano, & Codina 1967; Hoyle & Wickramasinghe 1970). In a then controversial paper, Clayton (1975) suggested supernovae condensed dust as a source of isotopic anomalies in ^{129}I , ^{26}Al , and ^{244}Pu isotopes found in meteorites. This view has since then gained wide acceptance, and SN-condensed dust is now accepted as the origin of a wide range of r- and p-process anomalies in meteorites (see review by Zinner 1996).

Various observational tests for the formation of dust in SNe were suggested. They fall

basically into three categories: (1) searches for the development of an infrared excess in the SN light curve, similarly to that observed in novae (Aiello, Bonetti, & Mencaraglia 1974; Falk, Lattimer, & Margolis 1977); (2) searches for evidence of extinction of background stars or nebular emission in the SN ejecta (Trimble (1977); and (3) searches for the IR emission from dust in the ejecta of young unmixed SNRs (Dwek & Werner 1981, Dwek & Arendt 1992).

SN 1979c and SN 1980k were the first SNe that were observed at near-IR wavelength and developed an IR excess about 7 - 9 months after their explosion (Dwek et al. 1983; Dwek 1983). The IR excess from SN 1979c could only be explained as an IR echo, since the IR luminosity was in excess of the extrapolated bolometric luminosity at the time the excess appeared (Dwek 1983), leaving only SN1980k as a possible site of dust formation. Attributed to an echo, the IR excess from both SNe was used to infer the mass loss rates for the progenitor stars (Dwek 1983), and found to be consistent with those required to explain the radio light curve from these SNe. Consistent with an echo interpretation, the IR observations of SN1980k provided therefore at most ambiguous evidence for the formation of dust in SN ejecta.

The explosion of SN 1987A provided the first direct and unambiguous evidence for the formation of dust in SN ejecta, as well as a new set observational criteria for the establishment of this fact. The first hint that dust was about to form in SN 1987A came from the detection of CO in its ejecta (Danziger et al 1991). The formation of CO molecules has in many cases been a precursor to the imminent formation of dust in novae (Gehrz et al. 1980). In addition, observers found also evidence for the presence of SiO molecules in the ejecta of SN 1987A (Roche, Aitken, & Smith 1991).

The formation of dust in SN 1987A occurred around day 530 after the explosion, and manifested itself in many different, and sometimes complimentary, ways: (1) in the evolution of a near- and mid-IR excess in the SN lightcurve that occurred concurrently with a drop in the UV-visual output from the SN (e.g. Bautista et al. 1995, and references therein). The total energy balance from the SN strongly favored a dust-formation scenario instead of an IR echo (Moseley et al. 1989; Dwek et al. 1992; Whitelock et al. 1989; Wooden et al. 1993); (2) in the evolution of the emission line profiles of various elements in the SN ejecta. Prior to the dust formation epoch these lines exhibited blue- and red-shifted profiles, characteristic of emission from a spherically symmetric expanding shell. Concurrent with the drop in the UV-visual output of the SN, line profiles developed an asymmetry, characterized by the diminution of the emission from the redshifted wing of the profile (Danziger et al. 1991). This line asymmetry persisted even on days 1862 and 2210 after the explosion (Wang et al. 1996). Absorption by intervening dust within the ejecta is the most logical explanation for this effect; (3) in the temporal decrease in the emission from various optical lines, such as Mg I] $\lambda 4571$ Å and [O I] $\lambda 6300,63$ Å. This drop was attributed to extinction by the newly-formed dust in the ejecta (Lucy et al. 1991); (4) in the depletion of various refractory elements from the gas phase. The drop in the IR line emission from [Si I] $1.65 \mu\text{m}$ (Lucy et al. 1991), or [Fe II] $26 \mu\text{m}$ (Dwek et al. 1992; Colgan et al. 1994) cannot be attributed to dust extinction, but rather to the possible precipitation of these elements from

the ejecta.

SN condensates were detected in the ejecta of the Crab nebula. Optical continuum images of the Crab (Fesen & Blair 1990) revealed numerous dark spots across the synchrotron nebula. The spectral properties and positions of these spots suggest that they represent dust extinction features instead of synchrotron emission holes in the filaments. A similar conclusion was reached by Hester et al. (1990) who attributed small-scale "red" features in the IR-to optical continuum ratio map to extinction by dust.

SN-condensed dust can also be detected from its IR emission. Specifically, dust present in the evaporative or turbulently-mixed interfaces of clumpy ejecta in a SNR cavity will be collisionally heated by the X-ray emitting gas, and can give rise to detectable IR emission (Dwek & Werner 1981). Infrared observations of Cas A with the *Infrared Space Observatory (ISO)* (Lagage et al. 1996) showed indeed clumpy IR emission from the remnant that is spatially correlated with the fast moving knots previously detected in optical emission lines (Fesen, Becker, & Goodrich 1988). IR 20 – 50 μm spectra taken from various position in Cas A, confirmed a dust origin for the emission (Moseley et al. 1997).

A difficult problem is the determination of the amount and composition of the dust that formed in the ejecta. Observationally, the 15 – 30 μm spectrum of SN 1987A was found to be featureless, and consistent with emission from either carbon or silicate type dust (Wooden et al. 1993; Moseley et al. 1989; Dwek et al. 1992). In principle, the dust composition can also be inferred from the selective extinction of the various emission lines in the SN ejecta. Furthermore, the evolution of the extinction with time can be used to determine changes in the dust composition and size distribution during the condensation period. Unfortunately, the quality of the data does not allow for such detailed analysis of the observations (Lucy et al. 1991).

Theoretically, the calculated composition of the dust depends crucially on the assumptions made regarding the degree and type of mixing in the SN ejecta. Lattimer, Schramm, & Grossman (1978) provided the first estimates of SN dust compositions by applying chemical equilibrium condensation calculations to various zones of an "onionskin" presupernova model. They did not consider the effect of mixing between the various zones of the ejecta. So in their calculations, zones were characterized by their C/O ratio, and depending on its value, either Ca- Ti- and Al-rich grains, or C-rich grains such as TiC, SiC, Fe₃C or CaS would form in the ejecta. Clayton & Ramadurai (1977) suggested that SN ejecta may contain various sulfide particles, such as TiS, MgS, or FeS, a prediction that may have been confirmed by the decrease in the IR line emission from Fe and S in SN 1987A after the dust-formation epoch (Dwek et al. 1992, Colgan et al. 1994). More speculatively, Nuth & Allen (1992) and Clayton et al. (1995) suggested SN produced diamonds as carriers of noble gas anomalies in meteorites.

SN 1987A provided theorists with a wealth of new information to predict the emerging dust composition. In particular, various lines of evidence suggested that the ejecta of SN 1987A was at least partially mixed. Consequently, Kozasa, Hasegawa, & Nomoto (1989) calculated the emerging

grain composition, mass, and size distribution for a variety of mixing conditions. In a subsequent paper Kozasa, Hasegawa, & Nomoto (1991) repeated their calculations under the assumption that the ejecta was completely mixed. Since the global C/O ratio in the ejecta is < 1 , all the carbon in this model is locked up in CO. Consequently, their results predicted the formation of grains with composition typical of O-rich environments, such as Al_2O_3 , Fe_3O_4 , and silicate grains.

All these calculations illustrate the sensitivity of the emerging dust composition on model assumptions, and the difficulty of predicting the dust composition even in the best studied supernova. It is clear however, that even if mixing did occur in SN 1987A, that it was macroscopic, rather than microscopic in nature (see §3.6.5 below). As a result, some regions in the ejecta are expected to remain C-rich and form carbon-rich grains. Furthermore, even if in some regions the C and O are mixed on a microscopic level, not all the carbon is expected to be locked up in CO. This results from the fact that the same mixing process responsible for the formation of CO can admix He^+ into the mixed layer, destroying the CO by the charge exchange reaction: $\text{He}^+ + \text{CO} \rightarrow \text{He} + \text{C}^+ + \text{O}$ (Liu, Dalgarno, & Lepp 1992).

The mass of the dust expected to form in SNe is equally uncertain. The IR emission from SN 1987A suggest a dust mass of $\sim (1 - 10) 10^{-4} M_\odot$ (Dwek et al. 1992; Wooden et al. 1993). However, the radiating dust may comprise only a small fraction of the total amount of dust formed in the ejecta. Most of the dust is probably cold and concentrated in optically thick clumps (Lucy et al. 1991). A more reliable estimate of dust mass can be obtained from the amount of extinction, or the drop in the line emission of various refractory elements in the SN ejecta. From these observations we can infer that most of the condensable elements precipitated efficiently from the expanding SN ejecta. If so, the expected dust mass can range from 0.1 to $1 M_\odot$.

5.1.5. *Following Explosive Conditions: Type Ia Supernovae*

To date there is no direct evidence for the formation of dust in Type Ia supernovae. There are some differences between Type Ia and Type II events which may inhibit the formation of dust in the former. Ejecta velocities, and the abundance of radioactive material are higher in Type Ia compared to Type II events. These may prevent the formation of dust for reasons similar to those that inhibit the formation of dust in fast novae (Gehrz 1988). However, Clayton, Arnett, Kane, & Meyer (1997) presented convincing arguments in favor of dust production in Type Ia events.

One group of the interstellar dust particles isolated and studied in meteorites consists of type-X SiC particles, with isotopic composition characterized by large excesses of ^{44}Ca (the radioactive decay product of ^{44}Ti), ^{28}Si , and ^{15}N . Clayton et al. (1997) argue that the assembly of dust with such composition in Type II events will require microscopic mixing of the ejecta, transporting various elements from different zones in the ejecta to the SiC-X dust condensation site. 2-D numerical and laboratory laser simulations of hydrodynamical explosion show evidence

for macroscopic mixing in the ejecta, but not the kind of microscopic mixing required to produce SiC-X grains.

In light of these difficulties, Clayton et al. (1997) suggested that Type-X SiC grains condense out of SN Ia events that explode with a cap of He atop their CO structure. The SiC particles condense out of ejecta that underwent explosive He burning in ^{14}N -rich matter, and the relative abundances of the C, Si, and trace N, Mg, and Ca match those of the SiC-X particles without the need to resort to ad hoc mixing scenarios.

The depletion of Fe in the general ISM is particularly sensitive to the ability for dust to form in SN Ia events. Iron is observed to be depleted with $\Delta(\text{Fe}) \gtrsim 0.70$ in refractory grain cores (Sofia, Cardelli, & Savage 1994). About one third of the interstellar iron is produced in SN Ia events. So if Type Ia events do not produce dust, the depletion of Fe (neglecting grain destruction by SNRs or Fe accretion in clouds) is expected to be $\sim 60\%$ at most. If Type Ia SN *do* produce dust, it will have important consequences for the composition of iron dust in the ISM. Since Fe is produced in large excess over any other refractory element including oxygen (Thielemann et al. 1993), it will likely condense out in pure metallic form (see § 3.8 below).

5.2. Dust Production Yields

We distinguish between stars with masses below $M_w = 8 M_\odot$, and those with masses above this value. For stars with $M \leq M_w$, the yield of the dust for each mass is simply determined by the C/O ratio in the ejecta. When the C/O ratio larger than unity, we assume that all the *excess* C is locked up in *carbon* dust. Its exact composition, whether graphite or amorphous carbon, is not important for the purpose of this paper. When the C/O ratio is less than unity, all the refractory elements: Mg, Si, Ca, Ti, and Fe, and about an equal amount of O *by number* are assumed to condense out of the gas. We refer to this dust as *silicate* dust. We will ignore the cases in which $\text{C/O} \approx 1$, since they are rare, and will not contribute substantially to the abundance of dust in the ISM.

To be more quantitative, we denote by $M_{ej}(A, M)$ be the mass of an element A in the stellar ejecta, and by $M_{dust}(A, M)$ the mass of A that is locked up in dust. Considering the refractory elements: C, O, Mg, Si, S, Ca, Ti, and Fe, we have adopted the following prescription to calculate the dust composition and production efficiency in the various stellar sources:

1) For stars with $M \leq M_w = 8 M_\odot$:

a) for stellar masses M in which $\text{C/O} > 1$ in the ejecta

$$\begin{aligned} M_{dust}(\text{C}, M) &= \delta_{cond}^w(\text{C}) \left[M_{ej}(\text{C}, M) - \frac{3}{4} M_{ej}(\text{O}, M) \right] \\ M_{dust}(A, M) &= 0 \quad \text{for } A = \{ \text{O}, \text{Mg}, \text{Si}, \text{S}, \text{Ca}, \text{Ti}, \text{and Fe} \} \end{aligned} \quad (22)$$

b) for stellar masses M in which $C/O < 1$ in the ejecta

$$\begin{aligned} M_{dust}(C, M) &= 0 \\ M_{dust}(A, M) &= \delta_{cond}^w(A) M_{ej}(A, M) \quad \text{for } A = \{ Mg, Si, S, Ca, Ti, \text{ and } Fe \} \\ M_{dust}(O, M) &= 16 \sum_{A=\{ Mg, Si, S, Ca, Ti, Fe \}} \delta_{cond}^w(A) M_{ej}(A, M)/\mu(A) \end{aligned} \quad (23)$$

where $\mu(A)$ is the mass of the condensing specie in amu.

2) For stars with $M > M_w = 8 M_\odot$:

$$\begin{aligned} M_{dust}(C, M) &= \delta_{cond}^{II}(C) M_{ej}(C, M) \\ M_{dust}(A, M) &= \delta_{cond}^{II}(A) M_{ej}(A, M) \quad \text{for } A = \{ Mg, Si, S, Ca, Ti, \text{ and } Fe \} \\ M_{dust}(O, M) &= 16 \sum_{A=\{ Mg, Si, S, Ca, Ti, Fe \}} \delta_{cond}^{II}(A) M_{ej}(A, M)/\mu(A) \end{aligned} \quad (24)$$

An equation identical to equation (25) was used for Type Ia SN, but with the $\delta_{cond}^{II}(A)$'s replaced with $\delta_{cond}^I(A)$'s.

The above equations assume that in stars with masses $< M_w$, the C and O in the ejecta are microscopically mixed so that the maximum possible amount of CO is formed. For higher mass stars and Type Ia SNe, the ejecta was assumed to be only macroscopically mixed, allowing for the formation of both, silicate and carbon type grains. In principle, we could have followed the detailed composition of the dust returned by each stellar mass into the ISM by choosing the right combination of δ_{cond} for each element. In practice, we chose $\delta_{cond}^w = 1$, and $\delta_{cond}(A)^{II} = \delta_{cond}(A)^I = 0.8$ for $\{A\} = \{ Mg, Si, S, Ca, Ti, Fe \}$, and equal to 0.5 for carbon. The $\delta_{cond} < 1$ values for Type II and Ia SNe presumably take into account the possible incomplete condensation of the elements in these objects, and the possible destruction of SN condensates during their injection into the ISM (see §6.1 below). The choice of the δ_{cond} 's for these objects is quite arbitrary.

All elements other than carbon are considered to be "silicate" grains, that is $M_{silicates} = \sum_{\{A \neq C\}} M_{dust}(A)$, although it is clear that in some cases sulfides or other grain composition may emerge from the ejecta. A particular case in point is the composition expected from Type Ia SNe. The models of Nomoto and coworkers give the following masses (in M_\odot) for the nucleosynthetic products from these objects: $\{C, O, Mg, Si, S, Ca, Fe\} = \{0.020, 0.130, 0.016, 0.150, 0.083, 0.015, 0.742\}$, where we omitted the noble gases. Clearly, Type Ia SNe produce more iron than can be bound with O or S to form various oxides or sulfides. Much of the iron from Type Ia SNe may therefore condense as pure iron. Nitrogen is neither expected to condense out in stellar or SN ejecta nor is it expected to accrete onto grains in the ISM (Barlow 1978c). We therefore ignored the evolution of N in the dust phase of the ISM.

5.3. Relative Production Yields by the Various Sources

Taking the C/O ratio as a criterion for the dust composition, the range of stars that form carbon dust depends on the initial stellar metallicity, as well as details of the dredgeup process (Renzini & Voli 1981; Frost & Lattanzio 1996 for a review). This is illustrated in Figure 6, which depicts the C and O production yield of stars in the $1 - 40 M_{\odot}$ mass range, as well as the C/O ratio in the ejecta for stars with an initial metallicities of $Z = 0.0040$ (Fig 6a) and $Z = Z_{\odot} = 0.020$ (Figure 6b). When the initial stellar metallicity is low, the amount of carbon needed to be dredged up to the surface in order to increase the surface C/O ratio to a value larger than unity is low. Consequently, the lower mass cutoff of stars that become carbon stars is $1.7 M_{\odot}$ at $Z = 0.0040$, and somewhat higher, $2.3 M_{\odot}$, at $Z = 0.020$. The upper mass cutoff on stars that become carbon stars is determined by the operation of the hot bottom burning process (HBB). In this process, the convective carbon rich envelope reaches down into the H-burning shell, and its bottom becomes hot enough for the CN cycle to process the carbon that was previously convected to the surface, into nitrogen. Stellar yields with $\alpha = 3/2$ in the RV81 tables include the effect of the HBB process, and the high mass cutoff for stars that become C-stars is $6.5 M_{\odot}$ at $Z = 0.0040$, and $5.3 M_{\odot}$ at $Z = 0.020$. Observationally, the initial mass range of main sequence stars that will become C-stars depends on the sample selection criteria. Jura (1991) finds a progenitor mass range between 1 and $5 M_{\odot}$ from observations of high-luminosity C-stars. Barnbaum et al. (1991) finds initial mass ranges between 2.5 and $4 M_{\odot}$ from an analysis C-stars with expansion velocities above $\sim 17.5 \text{ km s}^{-1}$. Kastner et al. (1993) find that progenitor masses are at least $2 M_{\odot}$ from a sample of distant low Galactic latitude AGB stars, and Groenewegen, van den Hoek, & de Jong (1995) derive a mass range of ~ 1.5 to $4 M_{\odot}$ from a comparison of observations with synthetic AGB evolution calculations. These values are similar to the theoretically derived values of RV81, and the differences should be a measure of the uncertainties in the calculated carbon dust abundance when compared with observations. For stars with masses above $8 M_{\odot}$ we allow, for reasons previously discussed, the formation of both, silicate and carbon dust.

Figure 7 depicts the SMS-weighted carbon and silicate dust yield of the stars in the $1 - 40 M_{\odot}$ mass range with initial metallicities of $Z = 0.0040$ (Fig 7a) and $Z = 0.020$ (Fig 7b), as a function of the initial stellar mass. The figure shows that carbon grains are predominantly produced in stars with masses in the $2 - 5 M_{\odot}$ range, whereas silicates are predominantly produced in higher mass stars. This fact has important observational consequences, since low mass stars return their ejecta to the ISM a considerable time after their formation (see §8.5).

6. GRAIN DESTRUCTION

6.1. Destruction During the Injection into the ISM

Circumstellar dust grains formed by quiescent mass loss may be altered during their injection phase into the ISM. They may be shattered, coagulate, or grow by accretion in the stellar outflow, but are mostly expected to survive the injection phase. This is not the case with SN condensates, which are injected at velocities exceeding $1,000 \text{ km s}^{-1}$ into a supernova cavity, containing shock-heated circumstellar/interstellar gas. *ISO* infrared images of the knots in Cas A vividly illustrate the perils supernova condensates can be subjected to after their formation. The clumpy ejecta containing the SN-condensed dust can evaporate or be turbulently mixed into the hot SN cavity gas where they will be subjected to destruction by thermal sputtering. Correlated SN may minimize the destruction of *interstellar* dust (McKee 1989), but may still be efficient in destroying newly-formed SN condensates. This aspect of grain destruction was previously overlooked, and can be incorporated into evolutionary models either by instantaneously updating the local metallicity of the ISM with the explosion of each SN, and calculating the effect of subsequent SNe on this enriched parcel of gas; or by reducing the condensation efficiency in the SN ejecta to take the destruction probability into account. A fraction of the SN condensates can escape destruction if the SN ejecta is mixed with the cold ISM before it evaporates in the SN cavity, or before subsequent SNe explode in its vicinity. The kinetic energy of the clump is then transferred via a cascade of turbulences to the ambient medium. The SN condensates may then just be subjected to shattering and coagulation processes, which will preserve the mass of refractory elements in the dust, instead of the thermal sputtering process in the SN cavity.

6.2. Destruction by Expanding Supernova Blast Waves

In the ISM, grains can be destroyed by thermal sputtering, evaporation in grain-grain collisions, thermal sublimation, and chemical sputtering. Of these processes, grain destruction by SNRs is the most important mechanism for cycling the dust back to the gas phase. Let $m_{dest}(A, r, t)$ be the total mass of element A that, initially locked up in dust, is returned to the gas by a single SNR expanding at location r and time t during its evolutionary lifetime. The rate at which A is returned to the gas is then given by:

$$\left[\frac{d\sigma_{dust}(A, r, t)}{dt} \right]_{SNR} = m_{dest}(A, r, t) \mathcal{R}_{SN}(r, t) \quad (25)$$

where $\mathcal{R}_{SN} = \mathcal{R}_{SNIa} + \mathcal{R}_{SNII}$, is the combined rate of Type Ia and Type II events in the Galaxy in units of $\text{pc}^{-2} \text{ Gyr}^{-1}$. Equation (26) can also be written in the form:

$$\left[\frac{d\sigma_{dust}(A, r, t)}{dt} \right]_{SNR} = \sigma_{dust}(A, r, t) \left[\frac{m_{dest}(A, r, t)}{\sigma_{dust}(A, r, t)} \right] \mathcal{R}_{SNR}(A, r, t) \equiv \frac{\sigma_{dust}(A, r, t)}{\tau_{SNR}(r, t)} \quad (26)$$

which defines the lifetime of element A against destruction by SNRs (Dwek & Scalo 1980; McKee 1989).

The value of τ_{SNR} plays a key role in calculating the interstellar depletion of element A . Calculations of τ_{SNR} involve knowledge of the physics of grain destruction by thermal sputtering and grain-grain collisions (Barlow 1978a,b; Draine & Salpeter 1979a; Jones et al. 1994; Tielens et al. 1994; and Borkowski & Dwek 1995), as well as the application of these grain destruction rates to interstellar shocks and SNRs (Shull 1977; Draine & Salpeter 1979b; Dwek & Scalo 1980; Jones et al 1996; McKee et al 1987; Seab 1987). In particular, McKee (1989), stressed the importance of the effect of correlated SNRs on calculating the grain lifetime. Dust evaporation by grain-grain collisions is the most difficult to model, yet becomes the dominant grain destruction mechanism during the radiative phase of remnant evolution, when most of the ISM is swept up. Grain destruction efficiencies by radiative shocks have been recently modeled by Jones et al. (1994), and global refractory grain lifetimes of ~ 0.4 and 0.22 Gyr have been estimated, respectively, for carbonaceous and silicate grains (Jones et al. 1996).

Grain destruction lifetimes are also expected to vary over the lifetime of the Galaxy. To explore this time dependency, we write m_{dest} , the mass of dust destroyed by a single SNR as:

$$m_{dest}(A, r, t) = \left(\frac{\sigma_{dust}(A, r, t)}{\sigma_{ISM}(A, r, t)} \right) \epsilon M_{SNR} \quad (27)$$

where M_{SNR} is the total mass of ISM gas swept up by the remnant during its lifetime, and ϵ is an average grain destruction efficiency. The grain destruction lifetime is then:

$$\tau_{SNR}(A, r, t) = (\epsilon M_{SNR})^{-1} \left[\frac{\sigma_{ISM}(r, t)}{\mathcal{R}_{SN}(r, t)} \right] \quad (28)$$

The amount of ISM mass swept up at a given velocity by an isolated SNR, does not depend on the ambient density, a simple consequence of momentum conservation during the late stages of its evolution. If we neglect the weak dependency of ϵ on the ISM density (Jones et al. 1996), then the quantity ϵM_{SNR} can be assumed to be constant with time. With this approximation, the lifetime of element A against destruction by SNRs can be written in terms of $\tau_{SNR}(A, (R_\odot, t_G)$, the current lifetime in the solar circle, as:

$$\tau_{SNR}(A, r, t) = \left[\frac{\sigma_{ISM}(r, t)}{\sigma_{ISM}(R_\odot, t_G)} \right] \left[\frac{\mathcal{B}(r, t)}{\mathcal{B}(R_\odot, t_G)} \right]^{-1} \tau_{SNR}(A, (R_\odot, t_G) \quad (29)$$

where we assumed that the SMS is spatially and temporally constant so that $\mathcal{R}_{SN} \propto \mathcal{B}$. Figure 8 depicts the the value of τ_{SNR} at the Galactic center and in the solar circle as a function of time.

6.3. Grain Destruction in the Starburst Galaxy M82

It is interesting to compare the theoretically derived grain destruction rates and timescales in our Galaxy (Jones et al. 1996) with those "observed" in external galaxies. An empirical grain destruction rate can be derived from [Fe II] $1.644\mu\text{m}$ $^4\text{D}\rightarrow^4\text{F}$ line transition in external galaxies. Fe has a first ionization potential of 7.87 eV, and is therefore easily ionized by the interstellar radiation field, provided it is not locked up in dust. Since Fe is expected to be depleted into dust, Greenhouse et al. (1991) suggested that the [Fe II] emission can be used as a tracer for supernova remnants, since they are the primary agents for grain destruction in the ISM. Fabry-Perot [Fe II] $1.644\mu\text{m}$ line images of M82 confirmed this idea (Greenhouse et al 1997). The observations showed that the [Fe II] emission is spatially correlated with known radio SNR in that galaxy (and not with H II regions). Their observations can be used to estimate the destruction lifetime of Fe in that galaxy.

To do so, we rewrite equation (26) for a galaxy as a whole in the form:

$$\tau_{SNR}(A) = \left(\frac{Z_{dust}(A)}{\dot{\mathcal{N}}_{SN}} \right) \left(\frac{m_{dest}(A)}{M_{ISM}} \right)^{-1} \quad (30)$$

where $\dot{\mathcal{N}}_{SN}$ is the SN rate in yr^{-1} , and M_{ISM} is the total ISM mass in the galaxy. In using equation (30), we will assume that the Fe^+ observed in the $1.644\mu\text{m}$ emission line represents the mass of iron that is returned by SNR to the gas phase, and that all the remaining iron is locked up in dust. A lower limit to the mass of Fe^+ can be derived by assuming that after the emission of the $1.64\mu\text{m}$ photon all the Fe^+ is instantaneously recycled back to the excited level. The observations of Greenhouse et al. give an extinction corrected [Fe II] $1.644\mu\text{m}$ luminosity of $1.1 \cdot 10^{40} \text{ erg s}^{-1}$ for an adopted distance of 3.2 Mpc. The A coefficient for the transition is $4.65 \cdot 10^{-3} \text{ s}^{-1}$ (Nussbaumer Storey 1988), giving a total mass of $\sim 0.083 M_{\odot}$ of Fe^+ in the galaxy. A more realistic assumption is that the Fe^+ is in LTE, in which case only $\sim 10\%$ of the ions will be in the excited level, giving an Fe^+ mass of $\sim 0.83 M_{\odot}$. However, LTE requires electron densities $\gtrsim 10^5 \text{ cm}^{-3}$, which are not likely to be met in the general ISM. For more realistic densities of $\sim 10^2 \text{ cm}^{-3}$, the relative population in the excited level is only $\sim 10^{-4}$, giving an Fe^+ mass of $\sim 800 M_{\odot}$. The ISM mass in the inner 6 kpc of M82 is estimated to be $\sim 2 \cdot 10^8 M_{\odot}$ in H I (Yun, Ho, & Lo 1993), and $\sim 2 \cdot 10^9 M_{\odot}$ in H_2 (Young & Scoville 1984). In deriving the H_2 mass Young & Scoville (1984) adopted a Galactic $\text{N}(\text{H}_2)/\text{N}(\text{CO})$ conversion factor, which may be an overestimate for M82 (Wild et al. 1992; Lord et al. 1996). Assuming a solar Fe abundance of $1.28 \cdot 10^{-3}$, a somewhat lower ISM mass of $10^9 M_{\odot}$, and a SN rate of $\dot{\mathcal{N}}_{SN} \sim 0.10 \text{ yr}^{-1}$ (Kronberg, Biermann, & Schwab 1981), we get that

$$\tau_{SNR}(\text{Fe}) \approx \left(\frac{1.28 \cdot 10^{-3}}{0.10} \right) \left(\frac{800}{10^9} \right)^{-1} \approx 2 \cdot 10^4 \text{ yr} \quad (31)$$

This value assumes that all the iron was initially depleted onto dust grains. However, even if only 10% of the iron was initially in the dust, so that, $\tau_{SNR}(\text{Fe}) \approx 2 \cdot 10^5 \text{ yr}$, this value would still be

significantly smaller than all current theoretical estimates, and significantly smaller than typical lifetimes of starbursts ($\sim 100 \cdot 10^6$ yr). We therefore must conclude, that the starburst region itself will end up mostly dust-free, and that a significant fraction of the infrared emission observed from starbursts is stellar radiation that is reprocessed by a foreground screen of dust.

7. GRAIN GROWTH IN THE INTERSTELLAR MEDIUM

In dense interstellar clouds grains can grow by the accretion of condensible elements onto *preeexisting* refractory cores. For simplicity we will assume that the dust particles consist of one type element \bar{A} , with a mass of μ_A . Let $n_g(A)$ be the number density of A in the *gas* phase of the ISM. The rate per unit volume at which the number of atoms, N_A , in the dust grows by accretion is given by:

$$\frac{dN_A}{dt} = \alpha \pi a^2 n_g(A) n_{gr} \bar{v} \quad (32)$$

where α is the sticking coefficient of element A to the grain, a is the grain radius, n_{gr} is the number number density of dust grains, and $\bar{v} = (8kT/\pi m_A)^{1/2}$ is the mean thermal speed of A in the gas. The rate at which the mass of the ISM dust phase grows by accretion can be written in terms of global Galactic quantities as:

$$\frac{d\sigma_{dust}(A)}{dt} = \alpha \left(\frac{\pi a^2}{m_{gr}} \right) \mu_A n_g(A) \bar{v} \sigma_{dust} \quad (33)$$

where m_{gr} is the mass of an individual dust grain. Elemental accretion takes place in high density molecular clouds ($n_H \gtrsim 10^3 \text{ cm}^{-3}$). The mass density of the element A can then be written in terms of the cloud density, n_c , as: $\mu_A n_g(A) = 2m_H n_c (1 - \sigma_{dust}(A)/\sigma_{ISM})$. Equation (21) can be rewritten in the form:

$$\begin{aligned} \frac{d\sigma_{dust}(A)}{dt} &= \frac{\sigma_{dust}(A)}{\tau_{accr}(A)} \\ &= \frac{[1 - \Delta(A)]}{\tau_0(A)} \sigma_{dust} \end{aligned} \quad (34)$$

where the depletion factor $\Delta(A) = \sigma_{dust}(A)/\sigma_{ISM}(A)$ is fraction of the element A that is locked up in the dust. The accretion timescale of element A onto dust grains is then

$$\tau_{accr}(A) \equiv \tau_0 / [1 - \Delta(A)] \quad (35)$$

where $\tau_0(A)$ given by:

$$\tau_0(A)^{-1} \equiv \alpha \left(\frac{\pi a^2}{m_{gr}} \right) \mu n_c \bar{v} \quad (36)$$

where μ is the mean molecular weight of the gas. The timescale τ_0 can be estimated by taking typical numbers for the various dust and cloud properties that determine the accretion timescale. For $0.1 \mu\text{m}$ radius grains with mass densities of $\sim 3 \text{ gr cm}^{-3}$, an accreting refractory of mass $\mu_A = 20 m_H$, molecular cloud densities of $\sim 10^3 \text{ cm}^{-3}$, and temperatures of $\sim 20 \text{ K}$, we get a value of $\tau_0 \approx 3 \cdot 10^4 \text{ yr}$. For $\Delta \approx 0.7$, that is, 70% of the element A is in the dust phase, we get $\tau_{accr} \approx 10^5 \text{ yr}$ for the accretion time. This timescale is short compared to the typical lifetime of a molecular cloud. From an extensive CO survey of regions around open star clusters, Leisawitz, Bash, & Thaddeus (1989) show that clusters with ages above $\sim 10^7 \text{ yr}$ retain only low mass molecular clouds in their vicinity. The smaller remaining pieces of the cloud complexes may have a longer lifetime, about $(1-2) \cdot 10^7 \text{ yr}$ (Larson 1987). Since the abundance of molecules is not zero in molecular clouds, this implies the existence of various mechanisms that eject newly accreted material back to the gas phase. Such mechanisms include normal evaporation following some cosmic-ray or UV induced stochastic heating event, explosive desorption, or grain-grain collisions (see Jenniskens et al. 1993 and references therein). The effects of these mechanisms were simulated in the laboratory by Jenniskens et al. (1993). In their experiments they exposed grain material to photons and ions in order to simulate the formation and evolution of grain mantles on interstellar grains. They estimate that interstellar dust particles accrete a layer of 200 \AA during their lifetime in a molecular cloud. For initial grain radii of $\sim 0.05 \mu\text{m}$, these results imply that the dust mass increased by a factor of ~ 2.7 , an e-folding time. The effective accretion timescale is therefore equal to $\sim 6 \cdot 10^7 \text{ yr}$, the lifetime they adopted for a typical molecular cloud.

However, at any given time, only a fraction of the total interstellar dust population resides in dense molecular clouds and is growing by accretion. To be applicable to equation (6) which describes the dust evolution averaged over the ISM phases, the effective accretion timescale derived above must be divided by the fraction of dust particles in molecular clouds. If we assume that this fraction is about $1/2$, then the ISM-phase averaged accretion timescale is $\sim (1 - 2) \cdot 10^8 \text{ yr}$, or about one-half the grain destruction time by SNRs.

The accretion timescale is not expected to be constant over the lifetime of the Galaxy. In our global approach, which consists of a one-phase ISM, the time dependence of τ_{accr} originates primarily from the changing mass fraction of molecular clouds in the Galaxy. The value of τ_{accr} derived for molecular clouds must therefore be divided by the fraction of the ISM mass that is in molecular clouds, that is, the ratio σ_{MC}/σ_{ISM} . We adopted a complicated prescription for the dependency of the stellar birthrate on the ISM and stellar mass densities (see eq. 15). However, if we assume that it is simply a linear function of the mass density of *molecular* material, then $\mathcal{B} \propto \sigma_{MC}$, giving $\tau_{accr} \propto \sigma_{ISM}/\mathcal{B}$. The attractive feature of this simplifying assumption is that the grain accretion and destruction timescales evolve identically in time.

Figure 8 depicts the accretion timescale as a function of time. Since τ_{SNR} and τ_{accr} both scale

with time as $\sigma_{ISM}(r, t)/\mathcal{B}(r, t)$, the current adopted τ_{accr}/τ_{SNR} ratio of $\frac{1}{2}$ is constant with time. Table 1 lists the current grain destruction and accretion timescales used in this paper.

8. MODEL RESULTS

We calculated the evolution of the disk, the ISM, the elemental and dust abundances by using a simple fourth–order Runge–Kutta integration procedure. Nucleosynthesis yields depend on the initial stellar metallicities, Z_* , and are therefore time dependent. To facilitate the numerical computations, we first calculated the evolution of the total metallicity, Z_{ISM} , using constant nucleosynthesis yields, obtained by averaging the yields at $Z_* = 0.0040$ and 0.020 . This gave us a first order solution for the evolution of Z_{ISM} with time. Nucleosynthesis and dust production yields, given as a function Z_* , were then mapped onto a time grid using the calculated $Z_{ISM} - t$ relation. The delayed recycling effect plays an important role in determining the evolution of the dust composition, and to ensure a smooth solution, we interpolated the stellar yields on a fine grid of 70 mass points in the 1 - 40 M_\odot mass interval. The results of our calculations are presented below.

8.1. Dust Sources and Sinks, and the Roles of Supernovae and Supernova Remnants

Figure 9 compares the dust production rate of various sources: Type II and Type Ia SNe, and low mass stars, to the destruction rate by astration. The various panels depict the silicate and carbon production rates at the Galactic center and in the solar circle. Values at the current epoch in the solar circle are listed in Tables 3 and 4. The tables shows that supernovae are the most important source of interstellar dust, contrary to the estimate of Gehrz (1989). The table shows considerable agreement between the production rates resulting from our detailed calculations and the observational values summarized by Jones & Tielens (1994). However, we find that novae dust production rates have been significantly overestimated in previous work. The tables also illustrates the role of supernovae and their remnants as, respectively, interstellar dust sources and sinks at the current epoch. Grain destruction rates are ~ 50 and $\sim 400 M_\odot \text{ pc}^{-2} \text{ Gyr}^{-1}$ for, respectively, carbon and silicate grains, whereas the production rate by both, Type Ia and II SN is ~ 1.5 and $\sim 10 M_\odot \text{ pc}^{-2} \text{ Gyr}^{-1}$ for carbon and silicate grains, respectively. Supernovae are therefore net destroyers of interstellar dust *at the current epoch*. However, at earlier epochs, when the ISM metallicities are below $Z \approx Z_\odot/40$, they inject more dust into the ISM than they destroy during the remnant stage of their evolution. The first generations of SNe in the universe play therefore an important role in the initial dust enrichment of the intercluster medium (Loeb & Haiman 1997) and of damped Ly α systems (Pei, Fall, & Bechtold 1991).

8.2. The Origin of the Elemental Depletion Pattern

An important test for dust evolution models is their ability to reproduce the elemental depletion pattern. Figure 10 depicts the fractional abundance of the major refractory elements that is locked up in dust for three cases. In the first case we assumed that grain destruction by SNR is *exactly* balanced by the rate of grain growth in molecular clouds. This is equivalent to setting the sixth, seventh and eighth terms in equation (6) to zero. The resulting depletion pattern (open squares) should then reflect the condensation efficiency in the various sources *and* the elemental dilution factor. This latter effect results from the fact that it is impossible to condense *all* the elements from the gas in *all* the sources, even if their condensation efficiency is unity. For example, even if carbon condenses out with a 100% efficiency in carbon stars, all other refractory elements, as well as the carbon locked up in CO molecules, are ejected back into the ISM in gaseous form. On the other hand, O-rich stars eject all the carbon back into the ISM in gaseous form. The absolute level of the depletion also depends on the elemental condensation efficiencies in Type Ia and Type II supernovae. In our calculations we adopted values less than unity for these efficiencies. Had we adopted values of δ_I or $\delta_{II} = 1$, the depletions would be closer to unity. We also did not attempt to introduce different condensation efficiencies for the different elements, thereby simulating a condensation temperature dependent nucleation process. With so many adjustable model parameters we don’t believe that such fine-tuning of the model is warranted at this time. The depletion trend looks therefore relatively flat for all elements heavier Mg.

In the second case we examined the maximum attainable depletions allowing for grain destruction, but not for grain growth by accretion, in the ISM (open diamonds). In the absence of any UV, cosmic ray, or shock processing of the accreted mantle into more refractory material, these depletions should reflect the maximum attainable depletions in refractory grain cores,.

In the third case we allowed grains to grow by accretion in molecular clouds (filled circles). The resulting depletions should be significantly higher than the previous case, since they now reflect core + mantle depletions. The accretion rates we adopted are somewhat higher than the grain destruction rates, however, they are limited by the amount of refractory elements available in the gas phase. Accretion rates balance the grain destruction rates by SNRs only when the depletions are about 50%. Consequently, the resulting depletions are somewhat lower than those in which all grain processing in the ISM was ignored (open squares). The depletion pattern is relatively flat above Mg, since we did consider any variations in the accretion timescales for the different elements. We point out that accretion caused a significant increase in the depletion of oxygen. In the absence of accretion, the amount of oxygen that can be incorporated in the dust is limited by the availability of other metals (Si, Mg, Fe) that it can chemically bind to in the gas. This constraint on the condensation efficiency of oxygen is expressed in equations (23) and (24). These constraints are removed in the accretion process, since oxygen can accrete onto dust as water ice.

Table 5 compares the calculated core and core+mantle depletions with observed depletions

summarized by Savage & Sembach (1996; their Table 7). A major uncertainty in determining the observed depletions is the set of reference abundances that should be used for the comparison. This uncertainty is reflected in the range of observed values quoted in the Table. The table shows that our calculated core + mantle depletions fall somewhat below the observed values. To get values that are essentially unity, we will have to assume unit condensation efficiency in the various sources, and that the accretion goes to completion in the molecular clouds. The table also shows that core depletions are significantly lower than the observed values. Since they are predominantly affected by the grain destruction efficiency in the ISM, we examined the dependence of these depletions on the grain destruction timescale.

The results of these calculations are shown in Figure 11, where we plot the core depletions of C, Si, and Fe versus the grain destruction lifetime by SNRs. The grain destruction lifetimes are normalized to the nominal values suggested by Jones et al. (1996): 0.4, and 0.22 Gyr for carbonaceous and silicate dust, and we adopted a value of 0.3 Gyr for iron dust. Also shown in the figure are the observed core depletions tabulated by Savage & Sembach (1996). The two entries given for each element (there is no data for C), correspond to the different results one obtains by using the sun or B-stars as the reference source for the undepleted abundances. The figure shows that the nominal grain destruction lifetimes ($\tau_{SNR}/\tau_o = 1$) are too short to explain the high observed core depletions of Si and Fe. Therefore, *a significant fraction of the refractory grain core must actually be accreted mantle material that has been processed either by UV radiation, cosmic rays, or interstellar shocks, into more refractory grain material.*

8.3. Evolution of the Dust Abundance

The dust abundance and composition plays an important role in determining the Galactic extinction law. Any evolution in these quantities will therefore result in a time varying Galactic opacity. This effect will have important consequences for determining the extinction corrections in external galaxies at various redshifts. Figures 12 and 13 depict the evolution of the ISM (gas + dust) and dust metallicity as a function of time at the Galactic center and in the solar circle, respectively. Also shown in these figures are the ratio of the two quantities, and the separate evolution of silicate and carbon grains.

At the Galactic center, the star formation rate peaks at 0.6 Gyr, and slowly declines thereafter. The metallicity rises accordingly rapidly until $t \approx 1$ Gyr, after which it rises more slowly to a value of 0.03 at the current epoch. The dust abundance follows that of the metallicity very closely, with $Z_{dust}/Z_{ISM} \approx 0.4$ throughout most of its evolution.

At the solar circle, the star formation rate peaks at a later epoch, and the metallicity of the dust and of the ISM are still rising. As at the Galactic center, the dust abundance follows that of the metallicity very closely, with $Z_{dust}/Z_{ISM} \approx 0.4$ throughout most of its evolution. This value is in close agreement with the observational value of $\approx 0.008/0.02 = 0.4$, that is inferred from IR

emission or extinction measurements.

8.4. The relation between Dust and ISM metallicity

In our model, the fraction of metals locked up in dust follows that of the overall ISM metallicity very closely, regardless of the star formation history of the ISM. This constancy between the dust metallicity and that of the ISM is a result of the fact that the grain destruction timescale and the accretion timescale are both proportional to $\sigma_{ISM}(r,t)/\mathcal{B}(r,t)$ (see eq. 29 and the discussion in §7).

Supporting evidence for our hypothesis that τ_{SNR}/τ_{accr} is only a weak function of time can be found in the radial gradient of the dust-to-gas mass ratio of our Galaxy (see Figure 14a). Using *COBE*/DIRBE observations of the large scale IR emission from the Galactic plane, Sodroski et al. (1997) constructed a three-dimensional model of the IR emissivity of the Galaxy. In their model they derive the dust abundance gradient, and find that it is equivalent, within the observational uncertainties, to the metallicity gradient in the galactic disk. Our model results confirm these results. They show that the dust and ISM metallicity are tightly correlated. The radial gradient in Z_{dust} is identical to that of Z_{ISM} , maintaining a ratio of 0.4 at all Galactic radii. Since each annulus in the Galaxy has a distinct star formation history, any time dependence in the τ_{SNR}/τ_{accr} ratio would result in a significant radial dispersion in the Z_{dust}/Z_{ISM} ratio, contrary to the results inferred from the infrared observations.

External galaxies can give additional insight into the dependence of Z_{dust} with Z_{ISM} . In a recent paper, Lisenfeld & Ferrara (1997) examined the relation between dust mass and gas metallicity in sample of dwarf irregular and blue compact dwarf galaxies. The gas metallicity was determined from the O/H ratio in these objects, and dust masses were derived from their 60 and 100 μm emission observed by the *IRAS* satellite. The sample presumably represents these galaxies at various evolutionary stages, as manifested in their range of metallicities. In their analysis, Lisenfeld & Ferrara (1997) found that $(\text{O}/\text{H}) \propto (M_{dust}/M_{HI})^{0.54}$. For comparison, we plotted our derived values of $(\text{O}/\text{H})_{gas}$ versus Z_{dust} . The results are shown in Figure 14b, together with the data that was presented in Figure 5 of Lisenfeld & Ferrara (1997). The curves shown in the figure represent the trend in three different regions of the Galaxy: the Galactic center, the solar circle, and the outer region of the Galaxy at $R = 15$ kpc. The results for the various regions are essentially identical, giving a relation of $(\text{O}/\text{H}) \propto (M_{dust}/M_{ISM})^{0.77}$. The trend is very similar to the data, but shows a systematic offset. Various factors can contribute to this effect: (1) the dust masses in the galaxies are systematically lower than their actual values. Dust masses were determined only from the 60 and 100 μm fluxes. The presence of emission from hot (equilibrium or stochastically heated) dust at 60 μm , can result in an overestimate of the dust temperature, and thus an underestimate of the dust mass. This effect can introduce a factor of $\sim 2 - 3$ error in the actual dust mass. This underestimate can be systematic, correlating with the abundance of hot dust, and perhaps with the star formation rate, and hence the metallicity of the system;

(2) the gas phase oxygen abundances in our model is systematically lower than observed in these galaxies. A significant fraction of the oxygen depletion is caused by accretion in the ISM. The sample of dwarf galaxies is characterized by the absence of dense molecular clouds, so accretion may not play an important role in the depletion of this element. The success at which Lisenfeld & Ferrara (1997) reproduced the observations *without* the inclusion of accretion in their model, may lend some support to this explanation; and finally (3) the range of metallicities in these galaxies may not represent a smooth evolutionary sequence, and actually reflect the stochastic nature of their chemical evolution. This effect will introduce a spread in their metallicity, and consequently in their dust abundance as well.

8.5. Evolution of the Dust Composition

Figure 15 depicts the evolution of the carbon and silicate dust mass surface density (Fig. 15a) and the evolution of the ratio of these two quantities (Fig 15b) as a function of time at the Galactic center (solid line), and in the solar circle (dashed line). The evolution of the silicate and carbon dust abundances reflects the result of the convolution of the stellar birthrates with the dust production yields. At all times the carbon-to-silicate dust mass ratio is less than unity since SNe, the main interstellar dust sources, produce more silicate than carbon dust. The changes in the relative abundances of carbon and silicate grains are the result of the delayed recycling of elements and dust back into the ISM by low mass stars. This delayed recycling effect becomes more evident when the evolution of the carbon-to-silicate dust mass ratio is depicted as a function of time (Fig 15b). The stellar birthrate at the Galactic center peaks before carbon stars turn off the main sequence. Consequently, the first generation of dust particles are primarily silicates. The birthrate at the solar circle is still increasing when the first carbon stars peel off the main sequence and start injecting carbon dust into the ISM. This results in a large increase in the carbon-to-silicate dust mass ratio during the main sequence turnoff of carbon stars. The ratio decreases after the last carbon–star progenitors leave the main–sequence.

These results have interesting implications for the possible classes of dust compositions in external galaxies or young star forming regions evolving from an initially metal–free gas. According to the models presented here, dust compositions, and hence extinction laws in external galaxies, should fall into three categories: (1) young galaxies or star forming regions should have overall low extinction characterized by a very weak 2175 Å extinction bump (which is commonly attributed to graphite grains). Such peculiar UV extinction has been observed with the *UIT* in the Small Magellanic Clouds (Prévot et al. 1984, Cornett et al. 1994). The lack of the 2175 Å absorption feature in the observed star forming field was attributed by these authors to the relatively young age of the system, and the relative scarcity of evolved carbon stars; (2) intermediate age systems, in which carbon stars are making a significant contribution to the ISM carbon abundance. The extinction law in these systems should be characterized by the presence of a strong 2175 Å extinction peak (compared to that of the Milky Way); and finally (3) a phase

where the extinction law should resemble that of the Milky Way galaxy. The main assumption in this simple classification scheme is that the stellar mass spectrum is the same in all these galaxies. However, the main underlying physical reasons that drive these differences are clear, and could be applied in the modeling and analysis of any galaxy or star forming region.

9. SUMMARY AND ASTROPHYSICAL IMPLICATIONS

We have developed a model for the evolution of the composition and abundances of the elements and the dust in the Milky Way galaxy. The model consists of three components: (1) a dynamical infall model for the evolution of the stars and gas in the disk; (2) a chemical model for the evolution of the elements; and (3) a model for the evolution of dust in which dust is formed in quiescent stellar ejecta, and Type I and Type II SN ejecta, and is destroyed by expanding SN blast waves. Accretion inside molecular cloud allows for grain growth in the ISM. Table 1 summarizes the various model input parameters.

The dynamical infall model starts from a bulge and disk which grow by mass infall from zero mass, to the currently observed bulge and disk mass surface densities.

The chemical evolution model reproduces the traditional observational tests summarized in Figure 4: the relative and absolute elemental abundances at the formation time of the sun, the age–metallicity relation, the G-dwarf problem, and the Galactic $[\text{Fe}/\text{H}]$ abundance gradient. Our model actually reproduced the latter test better than models that do not include dust, since we calculate the actually observed quantity, the *gas* phase abundance of Fe in the ISM, as a function of Galactic radius. Table 2 presents various model output parameters.

We calculated the dust yield from low mass stars, and Type II and Type Ia SNe. Silicates are primarily produced in high mass stars that become Type II supernovae, whereas carbon dust is primarily produced by stars in the $2 - 5 M_{\odot}$ mass range (Figures 6 and 7). The exact mass range of carbon stars depends on the initial stellar metallicity. Type Ia SNe produce iron in excess of any other heavy element. Condensation in Type Ia SNe will therefore result in the injection of a significant amount of Fe dust in a pure metallic form. The time dependence of the dust production rates of the various sources is given in Figure 9, and the current values are presented in Table 3.

Dust is destroyed by SNRs in the ISM, and we adopted the nominal grain destruction lifetimes calculated by Jones et al. (1996). Grain destruction rates are higher than the rate at which they are injected into the ISM by the various sources. Grain growth by accretion in molecular clouds plays therefore an important role in determining the dust mass, and we adopted an accretion rate that is two times faster than the grain destruction rate. Grain lifetimes depend on the ISM mass and the galactic SN rate, and are therefore evolving with time (Figure 8). We assumed that the accretion timescale has an identical time dependence, preserving the ratio of the grain destruction and accretion timescale as a function of time.

Type II SNe constitute the most important source of interstellar dust. SNR are the main source of grain destruction in the ISM, capable of destroying more dust than they produce. SN are therefore net destroyers of dust at the current epoch. However, early generations of supernovae are net producers of interstellar dust, since they expand in an initially dust-free or dust-poor interstellar medium.

We examined the origin of the elemental depletion pattern, to see if it reflects condensation in the sources, accretion in clouds, or destruction in the ISM. In principle, if interstellar processing can be neglected, condensation in stellar sources could explain the magnitude of the observed depletion pattern. However, even in this case, it would be too simplistic to expect the depletion pattern to correlate with the condensation temperature. When the idea was originally proposed by Field (1974), dust formation in Type Ia and Type II SNe was not an issue. Now that we know that these objects synthesize the bulk of the silicates and iron injected into the ISM, other effects, such as explosion energies, the amount of radioactivities, the degree of clumpiness in the ejecta, and dilution with gaseous ejecta from other sources can play major roles in determining the depletion pattern. All this is actually a moot point, since the exchange of material between the dust and gas phases of the ISM is so large, that all memory of the depletion pattern set up in the sources is erased in the ISM. The depletion pattern therefore reflects the efficiency at which the various elements stick to and remain on the grains. In the absence of any accretion in the ISM, the calculated elemental depletions should reflect the elements locked up in refractory grain cores. We examined the dependence of core depletions on grain destruction lifetimes, and found that even if these lifetimes are increased by a factor of four, the calculated core depletions will still be significantly smaller than the observed values. This suggests either that grain destruction lifetimes are even longer than adopted in this paper, or that a significant amount of the accreted mantle is reprocessed in the ISM into more refractory grain material.

The silicate and carbon dust production rates depend strongly on stellar mass, with carbon dust produced primarily in low mass carbon stars. The delayed recycling of the gas and dust by these stars back to the ISM has important consequences for the evolution of the dust composition in various regions of the Galaxy. The evolution of the ISM metallicity, and that of the carbon and silicate dust is presented in Figs. 12 (Galactic center) and Figure 13 (the solar circle). Overall, the evolution of the dust follows that of the metallicity. This is a simple consequence of the fact that the relative importance of the grain destruction and grain accretion timescale remains constant in time. We find that over most of the lifetime of the Galaxy, the mass of condensible elements locked up in dust is about 40% of the total mass of heavy elements in the ISM. However, the relative abundance of carbon-to-silicate dust depends on the birthrate history of the gas, and evolves as a function of time (Figure 15). From our models we can identify three epochs in the evolution of the dust composition: during the first epoch, the dust population is silicate rich, since carbon stars have not yet evolved off the main sequence; during the second epoch these stars inject carbon rich dust into the ISM, and the carbon-to-silicate mass ratio increases significantly; the last epoch starts roughly when the lowest mass carbon star evolved off the main sequence, and is marked by

an increase in the abundance of silicate dust. As the figure shows, not all regions of the Galaxy will undergo these phases, since they depend on the birthrate history of a given parcel of gas.

An important hypothesis made in this paper, is that the accretion lifetime has an identical time dependency as the grain destruction lifetime. The relative efficiency of these two processes is therefore constant over Galactic history, ensuring a tight correlation between the dust abundance and metallicity. This hypothesis can be tested by observing the radial dependence of the correlation between the dust-to-gas mass ratio and the metallicity. Large scale far-infrared observations of the Galactic plane suggest that the dust abundance follows the metallicity gradient. Since each annulus in the Galaxy has a distinct star formation history, it is hard to imagine such correlation if the relative efficiencies of grain destruction and accretions were widely time-variant. A plot correlating the dust mass with the oxygen abundance in a sample of dwarf galaxies shows a similarity in the trend of the model and the data, but also the presence of a systematic offset. This offset could be the result of the combined effects of an underestimate in the observed dust mass in these galaxies, the lack of significant oxygen accretion in their ISM, and the stochastic nature of star formation and chemical evolution in these galaxies.

If this hypothesis is indeed correct, then it is interesting to examine the possible processes that are responsible for keeping the relative efficiencies of these two processes in check. Observations of external galaxies may offer a clue. We examined the grain destruction timescales in M82, and found them to be extremely short, compared to the duration of the starburst. M82 is therefore not merely a starbursts galaxy, but an extremely efficient dust destroyer as well. With most of the metals back in the gas phase, the post starburst region can cool very efficiently, so that the epoch of grain destruction will be rapidly followed by an epoch of accretion onto any surviving grains. Even in the extreme case, in which all the dust in the starburst region is destroyed, the injection of newly synthesized dust by low mass star, or the admixing of dust from surrounding regions not affected by the starburst into the dust depleted region, will provide new nucleation centers onto which refractory gas phase elements can accrete. So the relative efficiency of the grain destruction and accretion processes may not be constant at any given instant in time, but constant on timescales averaged over a few hundred million years. The discussion above illustrates also the importance of including dust in chemodynamical models for the evolution of galaxies (e.g. Samlar, Hensler, & Theis 1997). These models consider the detailed interplay between star forming processes, metal production, stellar evolution, and the energetics and phase changes in the ISM. Interstellar depletions, and grain destruction will have an important effect on the cooling and energy balance of the ISM as well.

The results of this paper have important consequences for calculating the extinction in external galaxies. Young galaxies, or star forming regions that underwent a recent burst of star formation, will be silicate rich, and their extinction law may be characterized by the absence of the 2175 Å UV extinction bump that is widely attributed to the presence of graphite grains. The SMC may be such a galactic system. Our models, however, predict that some galactic systems, observed at just the right redshift, should have an anomalous extinction law (relative to the

average galactic one) characterized by an increase in the 2175 Å bump. Since graphite or carbon dust has a significantly larger UV-optical extinction, this result may have important consequence for the UV and optical appearance of these systems, and for the derivation of various intrinsic galactic properties that are affected by dust extinction.

Finally we would like to point out that the models presented here provide a framework for the self-consistent inclusion of the effects of dust in models for the population synthesis of galaxies.

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Table 1. Input Parameters for the Chemical Evolution of the ISM

Parameter	Description	Units/Comments
$\sigma_{tot}(r,t)$	total surface mass density of the disk (stars+ISM)	$M_{\odot} \text{ pc}^{-2}$
$\sigma_{ISM}(r,t)$	surface mass density of the ISM (gas+dust)	$M_{\odot} \text{ pc}^{-2}$
$\sigma_{ISM}(A,r,t)$	surface mass density of element A in the ISM	$M_{\odot} \text{ pc}^{-2}$
$\mathcal{B}(r,t)$	star formation rate	$M_{\odot} \text{ pc}^{-2} \text{ Gyr}^{-1}$
$M_{ej}(A, M)$	mass of element A ejected by star of mass M	M_{\odot}
t_G	age of the Galaxy	12 Gyr
k, n	powers of the relation $\mathcal{B} \sim \nu \sigma_{tot}^k \sigma_{gas}^n$	0.5, 1.5
ν	efficiency of the star formation rate	1 Gyr^{-1}
R_{SNIa}	the Type Ia SN rate	$\text{pc}^{-2} \text{ Gyr}^{-1}$
R_{SNII}	the Type II SN rate	$\text{pc}^{-2} \text{ Gyr}^{-1}$
R_G	total radius of the Galaxy	15 kpc
R_{\odot}	solar distance to Galactic center	8.5 kpc
σ_0	total surface mass density at Galactic center	$2.7 \cdot 10^3 M_{\odot} \text{ pc}^{-2}$
R_{bulge}	bulge scalelength	1.30 kpc
$\tau_{inf}(\text{bulge})$	infall timescale at $R \leq 2 \text{ kpc}$	1 Gyr
σ_{\odot}	total surface mass density at solar circle	$60 M_{\odot} \text{ pc}^{-2}$
R_{disk}	disk exponential scalelength	3.5 kpc
$\tau_{inf}(R_{\odot})$	infall timescale at $R = R_{\odot}$	4 Gyr
M_G	the total mass of the Galaxy (bulge + disk)	$6.5 \cdot 10^{10} M_{\odot}$
$\phi(M)$	the SMS normalized so that $\int_{M_l}^{M_u} \phi(M) dM = 1$	
M_l, M_u	mass limits of the SMS	$0.1 M_{\odot}, 40 M_{\odot}$
M_{b1}, M_{b2}	mass limits for binary systems	$3 M_{\odot}, 16 M_{\odot}$
M_w	lower mass limit for Type II SNe	$8 M_{\odot}$
$\sigma_{dust}(r,t)$	surface mass density of dust	$M_{\odot} \text{ pc}^{-2}$
$\sigma_{dust}(A,r,t)$	surface mass density of element A locked up in dust	$M_{\odot} \text{ pc}^{-2}$
$\delta_{cond}^w, \delta_{cond}^I,$ $\delta_{cond}^{II}, \delta_{cond}^{WR}$	the condensation efficiency of element A in the ejecta of stellar winds (w), Type I SN (I), Type II SN (II), and WR stars (WR)	see §5.2 for details
$\tau_{SNR}(R_{\odot}, t_G)$	average destruction timescale in ISM	0.4, 0.22, 0.3 Gyr for carbonaceous, silicate, and iron grains
$\tau_{accr}(R_{\odot}, t_G)$	average accretion timescale in ISM	$\tau_{SNR}/2$

Table 2. Output Parameters for the Chemical Evolution of the ISM

Parameter	Calculated	Observed
$\mathcal{B}(R_\odot, t_G) \text{ M}_\odot \text{ pc}^{-2} \text{ Gyr}^{-1}$	3.8	2–10 ^a
$R_{SNIa}(R_\odot, t_G) \text{ pc}^{-2} \text{ Gyr}^{-1}$	$3.65 \cdot 10^{-3}$	
$R_{SNII}(R_\odot, t_G) \text{ pc}^{-2} \text{ Gyr}^{-1}$	$2.44 \cdot 10^{-2}$	
$R_{Ia/II} = R_{SNIa}/R_{SNII}$	0.15	
Global Type Ia rate (per century)	0.22 yr^{-1}	0.3–0.4 ^b
Global Type II rate (per century)	1.4 yr^{-1}	0.45–2.2 ^b
β	0.0048	...
$\sigma_{gas}(R_\odot, t_G) \text{ M}_\odot \text{ pc}^{-2}$	8.8	5.7–7.0
$\sigma_{gas}(R_\odot, t_G)/\sigma_{stars}(R_\odot, t_G)$	0.15	
$\left(\frac{d\sigma(t)}{dt}\right)_{infall}(R_\odot, t_G) \text{ M}_\odot \text{ pc}^{-2} \text{ Gyr}^{-1}$	0.8	< 1.0
$Z_{dust}(R_\odot, t_G)$	0.0087	0.0073 ^c
$Z_{crb}(R_\odot, t_\odot)$	0.0017	0.0027 ^c
$Z_{sil}(R_\odot, t_\odot)$	0.0070	0.0046 ^c

^aRana (1991)

^bvan den Bergh & Tamman (1991).

^cWe compare here the calculated dust abundances at the time the solar system formed to the total abundances of refractory elements that can be locked up in dust, using solar system abundances. By doing this we circumvent the problems associated with the uncertainties in the determination of the current set of reference abundances.

Table 3. Dust Production Rates in the Solar Neighborhood at $t = t_G^a$

Stellar Source	This work		Jones & Tielens (1994)	
	carbon	silicate	carbon	silicate
<u>Quiescent mass loss</u>				
C-rich stars	2.8	...	2.1	...
O-rich stars	...	3.7	...	3.2
Wolf-Rayet stars	0.02	...	0.06	...
<u>Explosive mass loss</u>				
novae	$3 \cdot 10^{-3}$	$< 3 \cdot 10^{-3}$	0.3	0.03
Type II SNe	1.5	7.0	2	12
Type Ia SNe	0.09	3.5	0.3	2
<u>ISM processes</u>				
accretion in clouds ^b	52	380
total grain formation rate	56	390		

^aEntries are in units of $10^{-3} \text{ M}_\odot \text{ pc}^{-2} \text{ Gyr}^{-1}$

^bFor $\tau_{\text{accr}} = 0.2 \text{ Gyr}$ and 0.11 Gyr for carbonaceous and silicate grains, respectively

Table 4. Dust Destruction Rates in the Solar Neighborhood^a

Process	carbon	silicate
Star formation	7.8	32
Supernova shocks ^b	51	390
total grain destruction rates	59	420

^aEntries are in units of $10^{-3} \text{ M}_{\odot} \text{ pc}^{-2} \text{ Gyr}^{-1}$

^bFor $\tau_{SNR} = 0.4 \text{ Gyr}$ and 0.22 Gyr for carbonaceous and silicate grains, respectively

Table 5. Comparison of Calculated Elemental Depletions with Observations^a

Element	core	observed	core + mantle	observed
C	0.04	...	0.49	0.30–0.60
O	0.007	...	0.52	0.36–0.60
Mg	0.047	0.5–0.7	0.56	0.95
Si	0.048	0.13–0.4	0.56	0.94–1.0
S	0.048	0–0.1	0.56	...
Fe	0.07	0.65–0.78	0.54	1.0

^aObserved values are from Savage & Sembach (1996). The range in the observations reflects the range of values obtained by using solar or B-stars reference abundances

Fig. 1.— The stellar birthrate $\mathcal{B}(r,t)$ as a function of time. Shown are the stellar birthrates in the bulge, at $R=0$ (solid line), at the solar circle, $R = 8.5 R_{\odot}$ (dashed line), and the disk-averaged birthrate (thick solid line).

Fig. 2.— The Galactic birthrate history as a function of Galactocentric radius. The thin solid line is the stellar birthrate at $t = 2$ Gyr, and the thick solid line represents the birthrate at the current epoch, $t = 12$ Gyr. Curves intersecting the y-axis between these two curves represent the Galactic birthrates at $\Delta t = 2$ Gyr intervals, increasing from the top to the bottom curve.

Fig. 3.— The evolution of the mass surface density in the bulge (at $R=0$) and at the solar circle ($R = 8.5 R_{\odot}$), as a function of time. The total mass density (stars + ISM; solid lines) reaches a current value determined by the observed stellar density of the bulge and disk components of the Milky Way. The density of the ISM (dashed line) peaks at an early epoch, determined by the infall rate, and declines slowly thereafter.

Fig. 4.— Standard observational tests for chemical evolution models: (a) Predicted ISM abundances of select elements at $t = 7.45$ Gyr, normalized to their solar value. The horizontal dotted lines indicate where the values of the normalized abundances are a factor of two below and above solar value; (b) the evolution of the iron mass fraction, $Z(\text{Fe})$ as a function of time. Model results (solid line) are compared with the observational constraints; (c) the relative frequency of stars of a given metallicity versus metallicity (the G-dwarf problem); (d) the radial gradient of metallicity compared to observations. The inclusion of dust in the model actually improves the fit to the observations which only sample the iron that is in the gas phase of the ISM.

Fig. 5.— The Galactic supernova rates at the Galactic center and solar circle as a function of time. The Type II supernova rate is shown as a solid line, and the Type Ia rate as a dashed line. The relative rates were normalized to a value of $\text{SN Ia}/\text{SN II} = 0.15$ at the current epoch.

Fig. 6.— The carbon and oxygen yield of stars in the $1 - 40 M_{\odot}$ mass range for: (a) stars with an initial metallicity $Z = 0.0040$; and (b) stars with an initial metallicity $Z = Z_{\odot} = 0.020$. Also shown in the figures is the C/O ratio in the stellar ejecta. For $M < 8 M_{\odot}$, stars with C/O ratios > 1 in their ejecta were assumed to produce carbon dust, whereas stars with a C/O ratio < 1 , were assumed to produce silicate dust. Higher mass stars can produce both type dust particles, regardless of the C/O ratio in their ejecta.

Fig. 7.— The SMS-weighted yield of carbon and silicate dust as a function of initial stellar mass for: (a) stars with an initial metallicity $Z = 0.0040$; and (b) stars with an initial metallicity $Z = Z_{\odot} = 0.020$. The figure shows that most of the carbon is produced by low mass stars in the $\approx 2 - 5 M_{\odot}$ mass range, whereas silicate dust is produced predominantly in stars with $M \gtrsim 10 M_{\odot}$.

Fig. 8.— The evolution of τ_{SNR} , the grain destruction timescale by SNRs, and τ_{accr} , the timescale for grain growth by accretion, as a function of time. Both timescales have identical time dependence (see §6.2 and §7 in text) so their ratio is constant over Galactic history. The timescales are shown for the Galactic center and the solar circle.

Fig. 9.— A comparison of the dust production rate by various sources: SN II (solid line), stars with $M < M_{\odot}$ (dotted line), SN Ia (dashed line); to the destruction rate by astration (thick solid line). The various panels depict separately, the silicate and carbon production rates at the Galactic center and solar circle. Values at the current epoch at the solar circle are listed in Table 3. For sake of clarity, the grain destruction rate by astration was scaled down by a factor of 3.

Fig. 10.— The fraction of the elemental abundance that is locked up in dust for three cases: case 1 (open squares) assumes that the dust abundance is not altered by interstellar processes. These depletions should reflect the effect of condensation in the sources; case 2 (open diamonds) takes only grain destruction into account and ignores grain growth by accretion. The depletion in this case should reflect core depletions; case 3 (filled circles) includes the effect of grain destruction and accretion. These depletions should reflect core + mantle depletions in the ISM.

Fig. 11.— Core depletions are calculated as a function of τ_{SNR}/τ_o , where τ_o is the nominal value given by Jones et al. (1996), and equal to 0.22 Gyr for silicates, 0.4 Gyr for carbon dust, and we adopted an intermediate value of 0.3 Gyr for pure iron dust particles.

Fig. 12.— The evolution of the ISM metallicity Z_{ISM} , and dust metallicity Z_{dust} as a function of time at the Galactic center. Also shown are the separate contributions of carbon and silicate dust to Z_{dust} , and the ratio Z_{dust}/Z_{ISM} .

Fig. 13.— Same as Figure 12 in the solar circle.

Fig. 14.— (a) the carbon-to-silicate mass ratio (solid line), and Z_{dust} , the total dust-to-gas mass ratio (dashed line) at the present epoch, as a function of Galactocentric radius. Carbon dust is less abundant at the Galactic center, but the effect is small. The dust metallicity decreases as a function of radius tightly maintaining the relation $Z_{dust}(R, t_G) = 0.4Z_{ISM}(R, t_G)$ as a function of radius R . (b) model predictions for the dependence of the gas phase oxygen abundance on dust content, are compared to observations in Blue Compact Dwarf galaxies (X) and Dwarf Irregulars (triangles). Data were taken from Lisenfeld & Ferrara (1997). The figure is discussed in §8.4 of the text.

Fig. 15.— (a) The evolution of silicate and carbon dust at the Galactic center (solid line) and in the solar neighborhood (dashed lines) as a function of time. Peak abundances of the two dust populations reflect the result of the convolution of the stellar birthrate and the dust production yields; (b) The carbon-to-silicate dust mass ratio as a function of time at the Galactic center (solid line), and in the solar circle (dashed line). Dust abundance variations result from the combined effects of the stellar birthrate history, and the delayed recycling of carbon dust by low mass stars into the ISM. More details can be found in §8.5 of the text





























